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Active Solar Heating & Cooling

The best-known application of solar energy is to heat and cool buildings and to heat domestic water. Solar hot water heaters have long been used throughout the world. Israel, for example, has about one-third of its homes equipped with solar hot water heaters. Japan has several million in use. And some people in particularly sunny areas of the United States, such as south Florida, have used solar water heaters for more than 40 years.

The potential energy savings from the expanding use of solar energy for space and water heating is considerable since conventional heating and cooling of buildings currently consumes over 20 percent of the national energy budget.

Two distinct but complementary approaches are used to convert sunlight to usable heat energy. Active systems generally use the mechanical power of pumps and fans to collect, store, and distribute heat energy as it is needed. Passive systems, on the other hand, use conduction, convection, radiation, and the buildings themselves to trap, store, and transport energy. Hybrid systems combine both active and passive characteristics. Active heating systems usually provide 50 percent to 90 percent of a building's heating requirement.

Active systems use a collector, which is composed of an absorber plate to collect and transfer the sun's heat to a working fluid (either liquid or air), a translucent cover plate to prevent reradiation of heat, and insulation at the back of the collector. The fluid, heated as it passes through the collector, is then mechanically moved by fans or pumps to carry heat throughout the building, or is stored for later use.

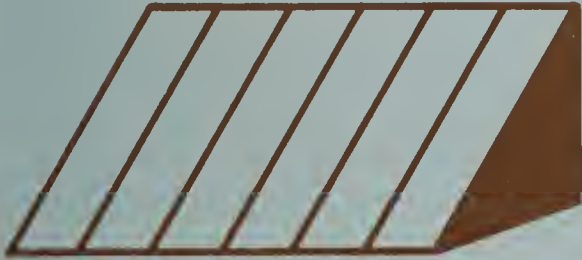
Since much of the thermal energy collected during daylight hours will be used at night and during overcast conditions, storage is required. Water is generally used as the storage medium for liquid systems, and rocks store heat for air systems.

In all, the active system consists of five main parts:

- a collector to capture solar radiation,
- a transport system to move heat from the collector to storage,
- a storage unit to retain heat for use at night or on cloudy days,
- a distribution system to move heat to living areas, and
- a system of controls to regulate the operation of the total system.

Active space heating systems should be combined with domestic hot water systems for maximum benefit. Solar hot water systems are a sound investment. They should last at least 20 years and a typical pay-back period (the point at which the money saved in utility bills equals the extra cost of installing a solar system) is from four to seven years.

Solar cooling systems use heat to operate either absorption chillers, similar to those in gas-fired refrigerators, or Rankine cycle systems (heat engines that generate electricity to run an air conditioner). Cooling systems require higher operating temperatures, and therefore more expensive collectors are needed. These systems are currently not cost-competitive, and research is ongoing to bring costs down.



Active Solar Heating & Cooling

SERI Report Summary

A Comparison of Six Generic Solar Domestic Hot Water Systems

Rob B. Farrington
L. M. Murphy
Darryl L. Noreen

Objective: Analyze six generic solar domestic hot water heating systems for cost effectiveness.

Discussion: Following a brief introduction, the most common solar domestic hot water (SDHW) system types and their basic operating principles are described. The following system types are included:

- single tank direct,
- double tank direct,
- single tank indirect,
- double tank indirect,
- double tank using air in the collectors, and
- single tank indirect thermosyphon.

The comparative performance of the systems is given. Studies conducted at the National Bureau of Standards and California State University in Sacramento were the major works used in this analysis. An analysis is presented that quantifies the extent to which parasitic energy (energy to

run fans, pumps, controls, and solenoid valves) reduces the net energy collected by the system. The economics of SDHW systems is then presented.

The cost effectiveness of the generic types is calculated using a simple relative ranking technique. Finally, the conclusion and recommendations derived from this study are presented.

Appendix A discusses geographical and reliability considerations for use of thermosyphon systems. Appendix B presents documentation for a newly conceived air thermosyphon SDHW system. Thirteen tables and 23 figures complement the report text.

Conclusions:

- Energy consumed by pumps and solenoid valves in the operation of SDHW systems was significant.
- Single tank systems outperformed double tank systems, because of large storage losses from double tank systems.

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- Direct systems were more efficient than indirect systems. However, the direct system consumed more energy due to the method of freeze protection used.
- The air system performed poorly, even with double-glazed collectors.
- The thermosyphon system was the most cost effective system tested.
- development and use of more energy efficient pumps and valves,
- use of additional insulation on storage tanks,
- development and use of energy efficient and reliable drain down devices for direct systems, and
- development of freeze protection for thermosyphon systems.

From these findings, the following are recommended:

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SERI Report Summary

The Analysis of Solar Collector Array Systems Using Thermography

Anthony Eden

Objective: Discuss the use of thermography to analyze large solar collector array systems under dynamic operating conditions.

Discussion: The report first presents a basic description outlining the theory and use of thermography, including color samples of the output. Then, the sites visited by the research team are discussed and the data gathered at each site are presented to show the possible analyses. The overall results are described, and the application and potential of thermography operational systems analysis and maintenance of large solar collector arrays are summarized.

The thermographic research presented in the report was conducted in Colorado and New Mexico at sites chosen from the National Solar Data Network and other instrumented locations. The systems examined included liquid and air flat-plate collectors with both selective and nonselective absorbing surfaces, evacuated tubes, passive houses, and compound parabolic collectors. The system sizes ranged from single-family dwelling heating systems to the Base Exchange at Kirkland Air

Force Base (930 m²). Various combinations of parallel and series plumbing configurations were also included. Sixty-two photographs illustrate the equipment used for analysis, the solar collectors at each site, and the results of thermographic analysis. In addition to the thermographs, three tables summarize the test data and results.

Conclusions: Thermographic analysis of most collector systems qualitatively showed relative temperature distributions that indicated balanced flow patterns. In three significant cases blocked or broken collector arrays, which previously had gone undetected, were discovered. Using this analysis, validation studies of large computer codes would aid in the examination of collector arrays for flow patterns or blockages that could cause disagreement between actual and predicted performance. Initial operation and balancing of large systems could be accomplished without complicated sensor systems not needed for normal operations. Maintenance personnel could quickly check their systems without climbing onto the roof and without complicated sensor systems.

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Solar Report Summary

Issued September 1983

Analysis of the Adsorption Process and of Desiccant Cooling Systems—A Pseudo-Steady-State Model for Coupled Heat and Mass Transfer

Robert S. Barlow

Objectives: To provide complete documentation of the development and validation of a computer program for predicting the performance of solar desiccant cooling systems. Also to provide a detailed description of the adsorption process and the physical behavior of desiccant beds to facilitate a more complete understanding of the operation of the dehumidifier in a desiccant cooling cycle and to provide information for an initial assessment of the potential for performance improvements through the development of advanced, high-performance components.

Discussion: A pseudo-steady-state model uses a new approach to analyzing transient coupled heat and mass transfer as they occur in adiabatic adsorption. The method uses simple equations from the theory of steady-state heat exchangers and mass exchangers and a straightforward finite difference procedure. This simplifies the mathematics, makes the model easy to adapt to investigate a variety of adsorption conditions and enables easier tracking of the physics of the process. The report includes a literature review of adsorption analysis and a review of available data and correlations of the properties of regular density silica gel.

The computer model was validated for a test device having initial uniform test bed conditions and constant

air parameters (single-blow) for both adsorption and desorption in packed beds of silica gel through comparison with experimental data primarily from the SERI Desiccant Test Laboratory.

Of importance is that adsorption comprises the progression of two heat and mass transfer waves through a desiccant bed and the differences between the behavior of thick beds, typically used for industrial adsorption applications, and thin beds, as in desiccant cooling systems. Predicted performance of thin beds is more sensitive to errors in transfer coefficients and desiccant property correlations. A detailed discussion of the adsorption process facilitates understanding of the operation of the dehumidifier in a desiccant cooling cycle.

The pseudo-steady-state model was incorporated into a computer program for the simulation of a complete desiccant cooling system. Parametric studies characterize the effect on performance of operating conditions, such as indoor conditions, outdoor conditions, dehumidifier wheel rotation speed, and regeneration temperature and the influence of individual component effectiveness on overall system thermal performance.

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Conclusions:

- A simple computer model for the adiabatic adsorption/desorption process has been developed and validated.
- A lumped gas-side mass transfer coefficient can be used for single-blow adsorption.
- Effective mass transfer coefficients must be reduced for cases of single-blow desorption, presumably because of a dynamic hysteresis effect in silica gel properties.
- The thermal performance of a desiccant cooling

system varies with indoor and outdoor temperature and humidity, and generally decreases as the difference between indoor and outdoor conditions increases.

- COPs above 1.0 are technically feasible if high-effectiveness dehumidifiers and heat exchangers are used.
- With high-performance components, the ventilation mode is clearly superior to the recirculation mode. Thermal COPs in the ventilation mode become relatively insensitive to outdoor conditions when highly effective components are used.

Solar Report Summary

Issued September 1983

Measured Performance Results: Low-Cost Solar Water Heating Systems in the San Luis Valley

Joel Swisher

Objective: To measure the thermal performance of a variety of low-cost solar water heating systems that are representative of the designs and components used in the San Luis Valley of southern Colorado.

Discussion: SERI monitored seven low-cost solar water heating systems in the San Luis Valley during the summer and fall of 1981. Measurements included solar radiation, outdoor temperature, collector inlet and outlet temperatures, domestic water temperatures, collector fluid and domestic water flow rates, and auxiliary water-heater energy use. The energy flows in each system were calculated, including collected solar energy, net solar and auxiliary heating, and gross auxiliary energy use. Collector and system efficiencies, coefficients of performance, and solar fractions were also calculated. The monitored systems represented a variety of low-cost solar water heating system designs and components. Five systems had site-built collectors, and four included low-cost, tank-in-jacket heat exchanger/storage tank com-

ponents. Two of the systems were air-to-water systems. The five liquid-based systems included a drain-down design, a propylene glycol-charged thermosiphon system, and three pumped-glycol systems. Four figures and four tables are included.

Conclusions:

- The pumped-liquid systems performed better than the thermosiphon and air-to-water systems.
- The site-built, liquid-based collectors performed as well as the commercial collectors.
- The thermosiphon system performed at low collector flow rates.
- Air leakage in the air-to-water systems decreased collector performance and promoted thermosiphon heat losses.
- The measured efficiency of each system depended on the hot water demand.
- Future work should include further detailed testing of low-cost, freeze-proof thermosiphon systems.

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Solar Report Summary

Issued January 1985

An Assessment of Dehumidifier Geometries for Desiccant Cooling Systems

Robert S. Bartow
Solar Energy Research Institute

Objective: To provide a technical assessment of dehumidifier geometries for desiccant cooling systems and to identify geometries that have the greatest potential of achieving performance levels that will make desiccant cooling systems economically competitive with conventional vapor-compression systems.

Discussion: Five dehumidifier designs are evaluated in this report—three from existing prototype cooling systems (from AiResearch, IGT, and IIT) and two (from UCLA and SERI) that have not yet been tested in a complete cooling system. The basic principles of heat and mass regenerators and the requirements of the solar cooling application have been combined to generate a list of desirable characteristics for dehumidifiers. The five designs are described and compared quantitatively; compared characteristics are related directly to the list of desirable characteristics. System performance is considered as well as isolated dehumidifier parameters.

This evaluation has been carried out in the context of the performance goals developed by Booz-Allen & Hamilton. The three completed prototypes each have design-point coefficients of performance (COPs) of roughly 0.5 to 0.6, whereas COPs near 1.2 may be needed to make desiccant systems economically

competitive. Highly effective, low-pressure-drop components are required to achieve this level of performance; therefore, the development of highly effective, low-pressure-drop dehumidifiers appears to be the most critical step.

A high-performance dehumidifier must have a high number of transfer units (Ntu) for heat and mass transfer. To achieve high effectiveness with a minimum of pressure drop, a dehumidifier geometry should have a high ratio of Stanton number to friction factor. A dehumidifier should also have a low resistance to moisture diffusion into and out of the desiccant particles and any solid material surrounding them.

Three figures and six tables are included.

Conclusions and Recommendations: The SERI wound-ribbon dehumidifier design has the highest ratio of Stanton number to friction factor and the lowest solid-side resistance to mass transfer of any geometry presently known to the author. These characteristics, along with the high surface area per unit volume, produce the highest Ntu and the lowest pressure drop of the five dehumidifier designs.

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Solar Report Summary

Issued January 1985

A Seasonal Storage Solar Energy Heating System for the Charlestown, Boston Navy Yard National Historic Park Phase II. Analysis with Heat Pump

Dwayne S. Breger
Allan I. Michaels
Argonne National Laboratory

Objective: To design a central solar energy heating plant, using seasonal heat storage and district heat distribution, for the National Historic Park Section of the Charlestown, Boston Navy Yard and to evaluate its thermal and economic effectiveness.

Discussion: A seasonal storage solar heating system using two existing underground concrete tanks was analyzed, with emphasis on the effect of including a heat pump in the system to extend the useful heat storage capacity of the tanks. The analysis was performed with MINSUN Version III, a computer simulation model written for seasonal storage systems. Three collector types were studied with and without a heat pump.

Eight tables and 35 figures are included. The compu-

ter code, and output data are presented in three appendices.

Conclusions: Inclusion of a heat pump improved thermal and economic performance for all collector types. Flat plate collectors showed substantial improvement due to their pronounced increase in efficiency at the lower inlet temperatures allowed by the heat pump. With the heat pump, all the collector types performed comparably; however, the flat plates were selected for the final system due to their low cost.

The final design system consisted of 2300 square meters of flat plate collectors with a heat pump. The system provides a solar fraction of 50 percent of the annual heat load, at an annualized cost of \$66.60 per million Wh of heat, which is competitive with the cost of conventional gas heat at \$0.05/kWh.

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Solar Report Summary

Issued June 1986

Objective: Present research recommendations for advanced and state-of-the-art active solar energy systems.

Discussion: In 1980, a Department of Energy (DOE) program plan was developed to address the reliability and maintainability (R&M) of active solar energy systems. The goal of this program was to hasten the removal of R&M obstacles to the widespread adoption of solar energy systems. The 1980 program plan recognized that other factors such as thermal performance, cost, and site constraints were also important components of an effective system. To maximize system effectiveness, the designer or manufacturer must often consider trade-offs between these various factors. In 1983, this program was renamed the Systems Effectiveness Research Program. As part of this program, the National Bureau of Standards was assigned the responsibility for developing research priorities to improve the effectiveness of active solar hot water and space-conditioning systems. To facilitate this, two meetings were held in August 1983. All major aspects of state-of-the-art active solar hot water and space-conditioning systems were discussed at one meeting. Only solar-control subsystems were considered at the other meeting.

Research Priorities for Improving the Effectiveness of Active Solar Hot Water and Space Conditioning Systems

Robert D. Dikkers
William J. Kennish
C. Byron Winn
William Huston

This report presents the recommendations resulting from both meetings. These recommendations deal with critical issues, including design, training, and performance. The report also presents recommendations for improving the reliability of advanced active solar energy systems. Various systems are discussed separately, and aspects of system and component reliability are addressed in each case.

Appendix B is a background paper entitled "Solar Heating and Cooling Control Subsystems" written by C. Byron Winn and Peter Armstrong. This paper describes needed solar heating and cooling controls research.

This publication contains one figure and four tables. Appendix A explains the development of a methodology to establish priorities for the Systems Effectiveness Research Program.

Conclusions: The report recommends the following areas for further research:

- State-of-the-art systems: control subsystems, materials, systems performance, technology transfer, and design tools
- Advanced systems: materials and components.

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Solar Report Summary

Issued December 1986

Objective: Measure the sorption properties of candidate solid desiccant materials for solar cooling applications under dynamic and equilibrium conditions, and different geometric configurations.

Discussion: Solar-driven solid desiccant cooling systems have received considerable attention as an alternative to standard vapor-compression systems. All the components in a solid desiccant system are reasonably advanced, except the dehumidifier; its performance is limited by the sorption desiccant capacity, sorption properties, and long-term stability under cyclic-operation conditions. Characterization of desiccants is important for understanding the dehumidifier performance and then improving the dehumidifier.

The report describes the test facility used to evaluate the effect of dehumidifier geometry on dynamic performance and its instrumentation. The methods used for the dynamic and equilibrium experiments are detailed, including the test results for a packed-bed and a parallel-passage geometry. The theory of perturbation chromatography is presented, along with its application to determining sorption capacities.

Experiments on Sorption Hysteresis of Desiccant Materials

A. Pesaran
F. Zangrando

Twenty-five figures and five tables are included in the report. Four appendices accompany the text. They describe (1) methods for data reduction, (2) preparation of the test cells, (3) operating procedures, and (4) the raw data collected at the test facility.

Conclusions: It was found that with an increase in air velocity and aspect ratio, the rotational speed of a parallel passage dehumidifier wheel should increase. Fundamental differences between the absorption/desorption processes were observed because of dynamic hysteresis accounted for in the model used to predict dehumidifier performance in solar cooling applications. The equilibrium results measured using the perturbation chromatography differed from published data. This was attributed to the possible invalidity of one of the basic assumptions in the theory of isotopic perturbation chromatography for silica gel-water vapor systems under the experimental conditions of the study.

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Solar Report Summary

Issued December 1986

Side-by-Side Comparisons of Evacuated Compound Parabolic Concentrator and Flat Plate Solar Collector Systems

Arthur E. McGarity
John W. Allen
William W. Schertz

Objective: Present results of tests conducted on evacuated compound parabolic and flat-plate collectors at Argonne National Laboratory (ANL).

Discussion: This report presents (1) the experimental comparisons of three different types of heating system collectors operated side by side for more than a year at Argonne National Laboratory, and (2) the results of simulated comparisons at ANL and other locations. The three collectors used were: a flat-plate collector with a black, chrome-coated absorber plate and one low-iron glass cover; an evacuated-tube, compound parabolic concentrator (CPC) collector with a concentration ratio of 1:1, oriented with tubes and troughs along a north-south axis; and an evacuated-tube CPC collector with a concentration ratio of 1:3 and one low-iron glass cover, with tubes and troughs oriented along an east-west axis. Details of system operation and instrumentation used to monitor performance are presented. Comparison of the three systems focus on system parameters, performance characteristics, and performance at various temperatures and weather conditions. The

trends observed in side-by-side testing are extended through computer simulation of each system. The two computer models ANSIM and TRNSYS are described, along with comparisons of measured and simulated results. The validity of the various methods of system testing and evaluation are also discussed.

Seventeen tables and forty-six figures accompany the text.

Conclusions: Analysis of test results indicates:

- CPC systems operate under cold and hazy conditions that are too adverse for flat-plate collectors.
- The flat-plate collector system is more efficient in warm weather; the standard CPC collector systems are slightly more efficient than the flat-plate collector system in cold weather. However, modeling indicates that a CPC system with improved absorber tubes, which became commercial after the tests were completed, would perform best in a collector with a north-south orientation.

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Bioconversion/Biomass

The term biomass refers to any material derived from living organisms and includes everything from manure to trees to algae. Plants capture and store solar energy directly through a process called photosynthesis. Animals and humans then tap this solar energy source by eating plants. The solar energy of photosynthesis can be released from biomass through a number of conversion processes. Useful fuels such as ethanol, methanol, hydrogen, charcoal, methane, and synthetic oils can be produced from biomass with byproducts such as food, fertilizers, and chemicals produced as a bonus.

Biomass can be converted to usable energy in many ways. Basically, there are two kinds of processes: *thermochemical conversion* and *biological conversion*. The first uses heat—sometimes in the absence of air—to produce chemical reactions. The best known thermochemical conversion is direct combustion. Burning wood provided 75 percent of the energy used in the United States 100 years ago. (This same amount of energy is today equal to about three percent of our annual national energy

use). Other thermochemical technologies include gasification, which releases bioenergy by heating wastes in a limited amount of oxygen, and pyrolysis, which breaks down biomass with heat, but without oxygen and at a lower temperature than is required for gasification.

Biological conversion is a chemical reaction caused by treating biomass with enzymes, fungi, or microorganisms. Two processes which produce either liquid or solid fuels include anaerobic digestion, the controlled decay of organic material in the absence of oxygen, and fermentation, by which carbohydrates are fermented and distilled to produce ethyl alcohol (ethanol). Ethanol mixed with gasoline produces gasohol.

Biomass is readily available in many waste materials and the supply could be greatly increased by proper management and the use of such techniques as energy farms. Biomass is not only a clean and safe fuel source but also a renewable and literally inexhaustible one.

SERI Report Summary

A Preliminary Report on the Agricultural Sector Impacts of Obtaining Ethanol From Grain

Donald I. Hertzmark

Objective: Describe preliminary results of an economic analysis of deriving ethanol from grain crops.

Discussion: The issues addressed in this report are the energy balance, balance-of-payments impacts, agricultural policy, and energy import impacts of potential ethanol production. In each area, preliminary analysis of available data is presented.

A brief appendix discusses the markets for fermentation by-products and the effects of increased ethanol production. Nine tables complement the report text.

Conclusions:

- Ethanol from grain can be a significant source of energy in the short term, at reasonable costs

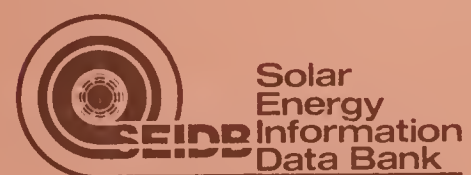
compared to other sources of liquid energy, if credit for by-products is included in cost calculations.

- A major effort to produce ethanol in the short run (prior to 1985) is not likely to significantly affect farm prices or exports.
- The production of at least one large-scale grain ethanol plant could be used to eliminate the current trade deficit in industrial ethanol.
- Further emphasis on grain ethanol production after the short run appears unwise due to the potential for adverse affects on agricultural trade.

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SERI Report Summary

Soil Fertility and Soil Loss Constraints on Crop Residue Removal for Energy Production

Silvio Flaim

Objective: Present estimates of the amount of crop residue that may be removed while maintaining maximum, long-term soil productivity.

Discussion: The report discusses soil fertility constraints on the collection of crop residues; i.e., what percentage of plant material can be removed before problems of nutrition depletion, excess water runoff, and evaporation and other problems are encountered. Soil loss constraints (limits defined by excess water and wind erosion) are examined. Included in the report are examples of residue management procedures which can be used to maximize the acceptable percentage of removed

crop residue while minimizing the negative impacts.

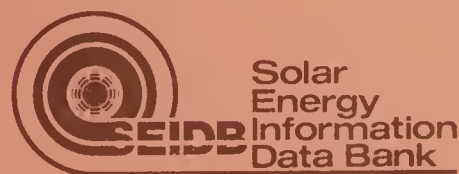
Conclusions:

- Retained residues required to limit wind and water erosion usually exceed residues required to maintain soil fertility.
- The detrimental effects of residues are negligible with conventional tillage practices.
- Conservation tillage practices release more residues for energy production than conventional tillage methods.

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SERI Report Summary

Agricultural Residue Collection Costs

Jan Dauve
Silvio J. Flaim

Objective: Examine costs that arise from harvesting agricultural biomass for use as an energy source.

Discussion: Five systems for collecting agricultural crop residues are examined: conventional bales, big round bales, big rectangular bales, stack wagons, and loose chop. Two sample farms in Iowa and Oklahoma are used as the basis for estimating collection costs. Costs are estimated using new machinery and do not represent average charges using existing harvesting equipment, nor opportunity costs for other farm activities.

Following a discussion of the characteristics of different crop residues, the report presents detailed cost estimates and an explanation of their derivation. To estimate costs each operation was divided into four factors of production: land, labor, capital and management.

Five explanatory tables and an extensive bibliography complement the text.

Conclusions:

- As an energy source, crop residues could be collected immediately using relatively common methods of hay harvesting.
- Residue harvesting equipment and techniques can be greatly improved.
- Collection costs varied from a low of \$12.63/ton for loose chop harvest of corn stover to \$25.85/ton for the rectangular bale system.
- Loose chop is not presently considered a viable alternative because of its high storage and handling costs.
- Big round bales are most likely to be used on small to large size farms.
- Giant rectangular bales are probably the best choice for very large farms.

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SERI Report Summary

The Market for Ethanol Feed Joint-Products

Donald Hertzmark
Brian Gould

Objective: Describe the findings of econometric estimation and simulation for the feed joint-product markets for ethanol produced from grain.

Discussion: The report is concerned with the impacts of food and feed joint products, distillers' grains, corn gluten meal and feed, and corn meal. Two different analytical techniques were used. Current price relationships among high-protein feeds and corn were estimated using single-equation econometric techniques on time-series data. In addition, simulations of the least-cost rations for a number of animals were obtained through linear programming methods based on a variation of the "feedmix" problem common to livestock operators.

A key assumption maintained throughout the analysis was that ethanol was produced in a biomass refinery that yielded ethanol, feed products, cooking oil, and sugars.

Thirty-five tables and two appendices accompany the main text.

Conclusions: The results of linear programming simulations of least-cost rations for cattle, poultry, and swine indicate that transport costs are an important component of the overall cost of a ration. An alcohol production program maximizing local production will be accepted with fewest upsets to feed prices. In hog-producing areas, the potential for local consumption appears limited due to the low productivity of distillers' dried grains (DDG) or gluten meal in the hogs' diet. Using DDG/gluten meal for 10 percent of animal protein requirements appears feasible when combined with local production of ethanol.

Increased use of DDG and gluten meal will mitigate upward pressures on corn and milo prices to the extent that these two crops are feedstocks for ethanol production.

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SERI Report Summary

A Review of Current Research on Hydrocarbon Production by Plants

H. M. Benedict
B. Inman

Objective: Assess the status of research and development in the area of plants that produce hydrocarbons which possibly can be used as a replacement for traditional fuels.

Discussion: The background behind growing interest in developing hydrocarbon-producing plant species and the relevant proposed or in-progress research is discussed in Section 1. With this review as a background, options are given for consideration by the Department of Energy (DOE) in support of a research and development program. The bulk of the report is divided into two sections. Section 2 outlines the steps required to reach commercial production of a hydrocarbon from the time a plant is found to contain such compounds, and describes ongoing or proposed research related to each step. Section 3 lists the organizations and individuals who are conducting or have expressed interest in

plant hydrocarbon research. Amounts and sources of funding are also indicated.

Conclusions: Interest in hydrocarbon-producing plant research is increasing. Industrial interest centers around the guayule plant and is supplemented by funds from DOE and the National Science Foundation.

Due to the infant state of technology in this area of research, it is not possible to predict or fully assess the potential contribution that plant hydrocarbons might make toward decreasing U.S. dependence upon petroleum.

However, the general impression from the review is that the major thrust of research should be toward the manufacture of petrochemical substitutes rather than fuel production.

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SERI Report Summary

Process Designs and Cost Estimates for a Medium Btu Gasification Plant Using a Wood Feedstock

Raymond E. Desrosiers

Objective: Determine the cost of processing steps common to all gasification plants using a wood feedstock to produce a medium-Btu gas and identify specific research areas.

Discussion: The research design incorporates a front-end handling system; a package cryogenic oxygen plant; a gas-cleaning train consisting of a spray scrubber, ionizing wet scrubber, and condenser; a wastewater treatment facility including a cooling tower and a package-activated sludge unit; and a Purox gasifier. The Purox gasifier and associated equipment were used since the system is nearer to commercialization than others which were considered.

Capital investment statements for three plant sizes (400, 800, and 1,600 oven-dry tons per day) are included. The total investment costs are \$9 million, \$15 million, and \$24 million respectively (1978 dollars). In each case, the oxygen plant represents about 50 percent of the total investment. Costs of package units were obtained from suppliers and used for both the oxygen and wastewater treatment plants.

Manufacturing costs are presented for each plant size at three feedstock prices: \$10, \$20, and \$30 per green ton; or \$20, \$40, and \$60 per dry ton.

Conclusions: For each pound of wood, 0.32 lb of oxygen is required and 1.11 lb of gas are produced. The heating value of the gas product is 300 Btu/scf. For each Btu of energy input (feed plus process energy) 0.91 Btu exits with the product gas.

The report recommends further study of the following systems:

Thermal cracking unit - A thermal or catalytic cracking of the pyrolysis oils and higher hydrocarbons exiting the reactor could significantly reduce processing costs and enhance the utility of the product as a syngas.

High pressure operation - Through a high-pressure operation and steam injection it may be possible to shift the gas composition to optimize the product as a syngas for SNG or methanol plants.

Dry-store front-end handling - Green wood chips contain 50 percent moisture. The gasifier operates most efficiently on a partially dried feed (20-30 percent moisture). Piles of green biomass can reach internal temperatures of 190F and self-dry to 23 percent moisture in one month due to chemical reactions such as resin polymerization and respiration. Advantage could be taken of this natural drying process if a front-end handling system incorporated storage of a 30-day inventory. The fire hazard is a limiting factor.

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SERI Report Summary

Issued June 1981

Survey of Biomass Gasification

SERI Staff

Objective: Present the technical background of biomass gasification, the present status of research and development, and recommendations for future work.

Discussion: This survey of biomass gasification was written to aid the Department of Energy (DOE) and the SERI Biological and Chemical Conversion Branch in determining the areas of gasification that are ready for commercialization and those areas in which further research and development should be most productive.

The survey has a number of important goals:

- to examine the properties and potential of biomass research related to gasification (chapters 1 to 4);
- to summarize the basic science of biomass gasification (chapters 5 to 7);
- to examine the present state of research, development, and commercialization of gasifiers (chapters 8 to 10);
- to discuss processes associated with gasification for gas cleanup and synthesis of other fuels from biomass gas (chapters 11 to 13);

- to determine means to expedite gasification technology commercialization (chapter 14); and
- to identify areas where research and development will be needed in an incentive gasification development program (chapter 15).

The survey compiles a wide range of technical and institutional information as an aid to engineers and decision makers.

Volume I is a synopsis and executive summary with eight figures and six tables, Volume II presents the principles of gasification along with one figure and two tables, and Volume III covers current technology and research and is supplemented with nine figures and two tables. Volume II contains chapters 1-7 and Volume III, chapters 8-15.

Conclusions:

- Both coal and biomass should be developed rapidly.
- Air gasifiers should be promoted immediately for commercialization at the present level of development for use in domestic and commer-

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cial heating, as well as process heating and power production for biomass industries.

- Large-scale oxygen gasifiers may play a prominent role in the conversion of municipal waste.
- Research and pilot work on pyrolytic gasifiers should continue. These are not as well developed as oxygen gasifiers, but they promote higher efficiencies and lower costs than oxygen gasification in production of medium-energy gas.
- Development of fast pyrolysis processes that give a high yield of olefins, which can be converted directly to gasoline or alcohol, should be a top priority.
- Carefully controlled laboratory efforts to determine the molecular details of pyrolysis should be continued.

- The scale of gasification plants should be studied immediately, and appropriate programs should be initiated to overcome the capital investment limitations of smaller scale. Assembly-line methods may be appropriate.

- A systems study should be made of biomass energy refineries to be used in conjunction with farming and forestry operations.

- For the longer term, economic analysis should be made to identify hybrid gasification schemes, including production of methanol using a combination of biomass and natural gas; joint electrolytic/gasification systems; and solar fast pyrolysis, in which high-intensity heat is supplied by solar collectors.

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SERI Report Summary

A Survey of Biomass Gasification Volume 1--Synopsis and Executive Summary

Solar Energy Research Institute Staff

Objective: Present, in summary form, the technical background on biomass gasification, the present status of research and development, and recommendations for future work.

Discussion: This survey of biomass gasification was written to aid the Department of Energy (DOE) and the SERI Biological and Chemical Conversion Branch in determining areas of gasification technology that are ready for commercialization, and areas in which further research and development should be most productive. The Executive Summary gives the highlights of each chapter in the survey for ready reference in condensed form.

The survey has a number of important goals:

- to examine the properties and potential of biomass research related to gasification (Chapters 1 to 4);
- to summarize the basic science of biomass gasification (Chapters 5 to 7);
- to examine the present state of research, development, and commercialization of gasifiers (Chapters 8 to 10);

- to discuss processes associated with gasification for gas cleanup and synthesis of other fuels from biomass gas (Chapters 11 to 13);
- to determine means to expedite gasification technology commercialization (Chapter 14); and
- to identify areas where research and development will be needed in an incentive gasification development program (Chapter 15).

The 400-page survey assembles a wide range of technical and institutional information as an aid to engineers and decision makers.

Eight figures and six tables accompany the text.

Conclusions:

- Both coal and biomass should be developed rapidly.
- Air gasifiers should be promoted immediately for commercialization at the present level of development for use in domestic and commercial heating, as well as process heating and power production for biomass industries.

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- The scale of gasification plants should be studied immediately and, where appropriate, programs should be initiated to overcome scale limitations.
- A systems study should be made of biomass energy refineries to be used in conjunction with farming and forestry operations.
- For the longer term, economic analysis should be made to identify hybrid gasification schemes including: production of methanol using a combination of biomass and natural gas; joint electrolytic/gasification systems; and solar fast pyrolysis in which high-intensity heat is supplied by solar collectors.
- Large-scale oxygen gasifiers may play a prominent role in the conversion of municipal waste.
- Research and pilot work on pyrolytic gasifiers should continue. These are not as well developed as oxygen gasifiers, but they promote higher efficiencies and lower costs than oxygen gasification in production of medium-energy gas.
- Development of fast pyrolysis processes that give a high yield of olefins which can be converted directly to gasoline or alcohol should be a top priority.
- Carefully controlled laboratory efforts to determine the molecular details of pyrolysis should be continued.

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SERI Report Summary

The Agricultural Sector Impacts of Making Ethanol From Grain

Donald Hertzmark
Daryl Ray
Gregory Parvin

Objective: Present the major economic issues involved in the conversion of grain to alcohol.

Discussion: The availability and cost of liquid fuels is currently the premier issue of energy policy. This report considers the role of renewable alcohol fuels as extenders of gasoline supplies and as substitutes for petroleum. In addition, the potential for substitution of other biomass fuels and chemicals is discussed. Several questions associated with the conversion of grains are reviewed in the report: the effects on supplies and prices, the net energy output of the conversion process, and the impacts on feed markets of joint products from ethanol conversion. The availability of land for crop production is also briefly discussed.

The accompanying appendix details the technical aspects of the energy analysis. Fourteen figures and 14 tables complement the text.

Conclusions:

- The amount of alcohol that can be produced in the next five years is not sufficient to cause serious upsets in the agricultural sector or in food prices.
- Careful scrutiny is required of policies that encourage the growth of energy crops on marginal lands.
- Marginal gasoline is the true competitor of alcohol. The use of average pricing has obscured the consideration of viable gasoline substitutes such as alcohol fuels.
- The development of land currently not used for agricultural production will not be necessary to promote greater production of grain.
- Mild crop disturbances here and abroad should not affect the feasibility of ethanol production in the near future.
- Carryover stocks of corn and soybeans will be reduced in alcohol production scenarios.
- Inefficient fermentation technology and low prices for joint products will make ethanol from grain costly, even relative to marginal gasoline.
- The cost of alcohol will rise more quickly than that of corn as greater production of alcohol leads to increases in corn prices.

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- The agricultural sector is sufficiently flexible to absorb large production requirements for fuels and chemicals to be produced jointly with food.
- The cost of providing high-protein feed to livestock will be reduced.

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SERI Report Summary

The Costs of Using Crop Residues in Direct Combustion Applications

Silvio Flaim
David Urban

Objective: To identify and analyze the costs involved in using crop residues in direct combustion applications.

Discussion: This report examines three direct combustion applications: on-farm grain drying, grain drying at a grain elevator, and using crop residues to fire utility boilers.

The examination of grain drying is limited to systems descriptions, selection considerations for drying equipment, and costs of three residue-fired systems currently available. The study of utility applications is limited to existing spreader stoker boilers.

First, the report discusses in detail the costs of residue-fired grain drying systems, including the costs of residue harvesting, transportation costs, and equipment capital and fuel costs. Then, several cost studies of crop residues used in utility applications are reviewed. Finally, the conclusions and recommendations from the study are presented.

Appendix A examines principles of combustion as a background for pollution control regulations and

how they pertain to equipment design and modifications required to burn crop residues. Appendix B sketches some pollution control regulations that pertain to solid fuel burners and emission control devices. Appendix C lists sample data relevant to the study. Fifteen tables complement the report text.

Conclusions:

- Crop residues are a viable alternative to coal as a boiler fuel, if the prices of new contracts for coal are compared with the current costs of crop residues and all environmental costs are included in the calculations.
- Direct combustion of crop residues is an immediate alternative to conventional fuels for grain drying.
- The potential use of crop residues as a utility boiler fuel depends on the specific characteristics of each boiler application as well as on the accessibility and cost of coal.

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SERI Report Summary

Feasibility Study for Anaerobic Digestion of Agricultural Crop Residues Final Report

Edward Ashare
Michael G. Buivid
Elizabeth H. Wilson

Objective: Provide cost estimates for the digestion of agricultural crop residues to produce fuel gas.

Discussion: Engineering economic analyses were performed for digestion of wheat straw, corn stover, and rice straw for small-farm, cooperative, and industrial scales. The small-farm scale assumed processing of the residue from the average size U.S. farm (400 acres), and the other sizes were two and three orders of magnitude greater, respectively.

Twenty-four figures and 42 tables accompany the text.

Conclusions: The production of fuel gas from these residues is at best economically marginal, unless a credit can be obtained for digester by-

products. The use of pretreatment techniques can double the gas output but will not be economically justifiable unless methods can be developed which use less chemicals or lower cost chemicals. Additional development is needed here. Low-cost "hole-in-the-ground" batch digestion results in improved economics for the small farm but not for the cooperative and industrial systems.

Continued development is important in the areas of autohydrolysis and chemical pretreatment of agricultural crop residues to improve fuel gas yields. Low-cost controlled landfill batch digestion techniques need to be developed for the small farm. The value of crop residue digestion by-products as fertilizer and feedstock needs to be determined.

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SERI Report Summary

Decisionmaker's Guide to Wood Fuel for Small Industrial Energy Users Final Report

Michael P. Levi
Michael J. O'Grady

Objective: Present, for plant managers and engineers, detailed material on the technical and non-technical issues involving the use of wood as an industrial fuel.

Discussion: This handbook publication presents the technology and economics of various wood energy systems available to the small industrial and commercial energy user. The handbook is divided into two parts. The first part is an overview of the different aspects of wood energy, beginning with the chemistry of wood combustion and continuing through such topics as fuel storage, fuel handling, pollution abatement, and others. It is designed for the reader who is interested in general information. The second part gives detailed information for each of the topics covered in the first part. The authors point out that since no

two situations are alike, fuel amounts, types, costs, space requirements, and capital needs will vary from facility to facility. The handbook is not designed to tell the reader how to design and install a wood fuel system. Rather, it is designed to help a plant manager or engineer to become more familiar with wood fuel systems and to make informed decisions about the potential of wood as a fuel.

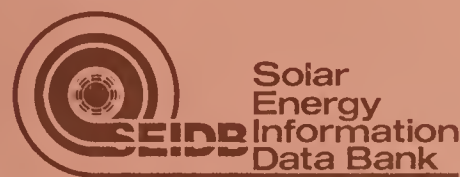
Appendix A is a directory of suppliers. Appendix B is a bibliography on wood as a fuel, and Appendix C presents a glossary of terms.

Conclusions: This document covers a wide variety of topics, including storage and handling of materials, economics, combustion equipment, and environmental concerns associated with the use of wood as a fuel.

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SERI Report Summary

Predicting Methane Fermentation Biodegradability Final Report

Jeffery A. Chandler
William J. Jewell

Objective: Evaluate the adequacy of analysis procedures used for predicting the digestibility of animals feedstuffs for predicting a material's methane fermentation biodegradability.

Discussion: For over 15 years, animal nutritionists have been successfully predicting animal feedstuff digestibility based on feedstuff composition. Their predictive model uses a set of fiber analyses using detergent extraction of substrate organic constituents. In the present study, these fiber analyses and the digestibility model were used to determine their potential for rapidly predicting methane fermentation biodegradability. The results of these short-term analyses were

compared to long-term batch fermentation tests, using a number of subject materials.

Conclusions: Lignin was found to be the major factor controlling substrate biodegradation. Four models predicting substrate biodegradability were constructed and compared. Predicting biodegradability based on volatile solids lignin content was found to be the most effective model. This model was simple to use and produced results with accuracy comparable to those of methods requiring 100 days for analysis. The analyses required by the lignin model can be completed in one day.

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SERI Report Summary

Report on the Design and Operation of a Full-Scale Anaerobic Dairy Manure Digester: Final Report

Elizabeth Coppinger
Jack Brautigam
John Lenart
David Baylon

Objective: Detail the experiences encountered during the two-year operation of a 200-cow-unit dairy manure digester.

Discussion: A full-scale anaerobic manure digester was operated and monitored for two years at the Monroe State Dairy Farm (Monroe, Wash.) under funding from the U.S. Department of Energy Fuels from Biomass Branch.

Various operating procedures and system performance characteristics are discussed. Test results on an influent/effluent heat exchanger are presented.

Results of biological stability monitoring are given. Gas production rates and system net energy

are analyzed. The economics of anaerobic digestion are evaluated on the basis of various financing options, design scales, and expected benefits.

Twenty-eight figures present details of the plant design and system performance. Seven tables give detailed performance and economic data. Two appendices include technical background information on the calculations discussed in the body of the report.

Conclusions: Under many circumstances, digesters are technically and economically feasible today.

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SERI Report Summary

Biotechnology for Producing Fuels and Chemicals from Biomass Recommendations for R&D Volume 1—Synopsis and Executive Summary

Ruxton Villet

Objective: Provide a framework for the design of a national program of contracted research in biotechnology for the production of fuels and chemical feedstocks from biomass.

Discussion: Specific research and development (R&D) project areas that will help advance biotechnology are identified in Volume I of this report. These areas are discussed in greater depth in Volume II (to be published), with detailed references from science and engineering literature. Volume I begins with a general discussion of biotechnical R&D and then goes directly into recommendations for future R&D programs.

Conclusions: Previously developed fermentation technology should be revived with emphasis on improved efficiency to bring processing costs to a competitive level, and new biotechnological processes should be developed. For both the near and

long terms the mutually supporting research objectives, genetic engineering of microorganisms to improve the biotechnological potential and the commercialization of these new strains of microorganisms, should be stressed. Biotechnological R&D should be organized as an integrated effort of biochemical engineering, microbial genetics, and biochemistry.

To facilitate management of the national R&D program, contractual work should be arranged under the following categories:

- microbial R&D;
- biotechnological process evaluation, control, and optimization;
- biotechnological process development and demonstration; and
- design and development of separation processes.

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SERI Report Summary

Research into the Pyrolysis of Pure Cellulose, Lignin, and Birch Wood Flour in the China Lake Entrained- Flow Reactor

James Diebold

Objective: Report results of experiments on rapid pyrolysis of powdered cellulose, pure lignin, and birch wood flour in a China Lake tubular, entrained-flow pyrolysis reactor.

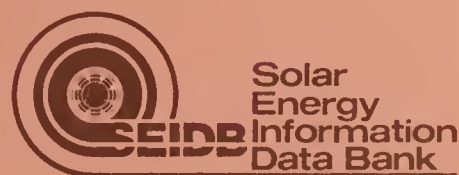
Discussion: The goal of these experiments was to produce gases containing significant quantities of ethylene and other olefins.

Conclusions: Pure cellulose and wood flour did pyrolyze to produce primarily gaseous products containing significant amounts of ethylene and other useful hydrocarbons. During attempts to pyrolyze powdered lignin, the material melted and bubbled to block the reactor entrance. Pyrolysis of cellulose and wood flour yielded very little char and tar than compared to that produced with processed municipal trash. The char appeared to be agglomerated spheroids rather than charcoal.

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SERI Report Summary

Issued June 1981

Preliminary Energy Balance and Economics of a Farm-Scale Ethanol Plant

Dan Jantzen
Tom McKinnon

Objective: Examine the energy balance and economic viability of a farm-scale grain-to-ethanol plant in Campo, Colo.

Discussion: SERI representatives evaluated the energy balance of a farm-scale grain-to-ethanol plant operated by the Schroder family of Campo, Colo. Measured energy inputs to the system were diesel fuel and electricity. System boundaries for the analysis were the grain bins on the farm to the ethanol tanks and stillage waste pile on the farm. The analysis was performed for the currently

operating plant, as well as for an improved plant now under construction at the farm.

Four figures accompany the text.

Conclusions: The reported analysis indicated a total processing energy requirement of approximately 29,000 Btu's per gallon of 190-proof ethanol. Preliminary economic analysis for a 400,000-gallon-per-year plant thus predicts a very favorable return on investment when by-product credits are considered.

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SERI Report Summary

Issued June 1981

Feeding Value of Dried Distillers' Grains (DDG) in Beef Feedlot Rations Final Report

G.M. Ward
J.K. Matsushima

Objective: Describe the findings of feeding trials designed to determine the suitability of dried distillers' grains as a major component of cattle rations.

Discussion: Dried distillers' grains (DDG) replaced corn in steer feed for the Colorado State University feedlots in Fort Collins, Colo. Eighty-four steers weighing an average of 760 pounds were allotted to six pens of 14 head each. At the beginning of the experiment, each steer was weighed, tagged, wormed, and implanted with Synovex-S. The cattle were started on a standard diet of corn silage, flaked corn grain, beet pulp, and protein supplement. Then the diet was divided into three groups, with two replicates per group, as follows:

- two pens—control,
- two pens—15 percent DDG, and
- two pens—30 percent DDG.

After four months, the experiment was completed, the cattle were slaughtered, and the carcasses were USDA-inspected.

Conclusions: There were no important differences among the three groups of animals. However, the DDG diets produced a thicker fat cover than the control diet, and marbling scores were higher for the control and 30-percent groups than for the 15-percent group.

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Solar Report Summary

Issued November 1982

Alcohol Fuels Activities at the Solar Energy Research Institute — 1981

Alcohol Fuels Program Office

Objective: Present briefly the 1981 Alcohol Fuels Research Program at SERI.

Discussion: The SERI Alcohol Fuels Research Program consists of both in-house and subcontracted research funded by the Office of Alcohol Fuels of the U.S. Department of Energy. The program includes research on ethanol and methanol production systems and on novel alcohol uses. Processes with higher efficiencies and lower production costs are the major goals, and the ultimate objective of the pro-

gram is for alcohol fuels from biomass to become a major contribution to the nation's supply of liquid fuels.

Section I gives an overview of the research program. Sections II and III present fact sheets on the individual research tasks undertaken in Fiscal Year 1981 for the in-house and subcontracted portions of the program, respectively. Five figures and two tables are included.

Conclusions: No conclusions are cited.

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Solar Report Summary

Issued June 1986

Biological Conversion of Biomass to Methane

Final Subcontractor Report
1 January 1980 to 31 March 1981

Paul N. McFarlane
John T. Pfeffer

Objective: Determine the effectiveness of thermochemical treatment to enhance the rates of production and yields of methane from crop residues by fermentation.

Discussion: The production of biogas by anaerobic digestion of untreated crop residues is economically unattractive as a high rate methane fermentation process because of poor conversion efficiencies. However, the pretreatment of residue prior to fermentation has been found to improve substantially the biodegradability of the ligno-cellulose fibers. Thermochemical pretreatment using sodium hydroxide (NaOH) at temperatures up to 200°C (392°F) has been found to be effective in laboratory-scale studies.

In this study, the effectiveness of thermochemical pretreatment in 0.775 cubic-meter fermentation reactors was evaluated for corn-stover and wheat-straw feed slurry solids. The pretreatment temperature and duration, the slurry concentration, and the NaOH

concentration were varied to determine their respective effects.

Fourteen figures and 26 tables are included. Three appendices contain detailed study data.

Conclusions: Solids concentrations and pretreatment temperature did not significantly affect the gas yield from corn stover. Increase in the NaOH dosage and pretreatment time increased gas yield until inhibitory conditions developed. NaOH levels above 7.33 percent and pretreatment times greater than 120 minutes caused severe inhibition of methanogenic bacteria in the processing of corn stover. Methanogenic microorganisms were inhibited under all pretreatment conditions in wheat straw processing.

High-rate methane fermentation of corn stover and wheat straw does not appear to be improved economically by the pretreatment conditions examined during the course of this study.

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Issued November 1982

Biomass Feedstocks for Petrochemical Markets: An Overview and Case Study

Silvio J. Flaim
Andrew M. Hill
Dan Lippe

Objective: Present an overview of the petroleum/ petrochemical industries and of refinery trends, along with a case study of methanol production for captive use in formaldehyde manufacturing.

Discussion: In this report, a method of analysis is developed for identifying target chemicals for which products from biomass feedstocks may substitute. Methanol was chosen for the case study, because it is made from natural gas with well-known and relatively uniform technology; no significant joint-product cost allocations are required. The report presents an overview of the petroleum/ petrochemical industries along with a general discussion of refinery trends. It also contains a case study covering the production of methanol for use in manufacturing formaldehyde.

Two figures and eight tables are included. Three appendices present general material for market assessment of several petrochemicals that may be obtained from biomass resources. Appendix A is an overview of petrochemical supply and demand trends. Price and cost forecasts for major petrochemicals are given in Appendix B. Appendix C describes coal and biomass gasification technology.

Conclusions: Biomass provides an alternative to imports of petroleum, natural gas, and their derivatives, should the United States become a net importer of petrochemicals. The forest products industries consume large quantities of methanol to produce formaldehyde-based adhesives. The large biomass resources near existing formaldehyde production facilities offer an attractive resource base for methanol production. Thus, wood-derived methanol appears well-matched for derivative products, such as formaldehyde.

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Issued November 1982

Economic Impacts of Ethanol Fuels from Crops

Donald Hertzmark
Daryl Ray
James Richardson

Objective: Determine the impacts of ethanol on prices and quantities of agricultural crops.

Discussion: Ethanol from agricultural crops and other renewable resources represents a small but strategic supplement to the liquid fuel supplies of the United States. The initial feedstocks for this fuel source involve an equally strategic set of products—grains. The results of simulations of agricultural production of ethanol feedstocks from grains and sugar crops are presented to address the impact of this competition between the need for fuels and the need for food crops. Production levels of up to five billion gallons of ethanol per year were simulated using various combinations of corn, high-energy sorghum, and sugar beets.

Twenty tables are included in the report.

Conclusions: The major results of the study show that:

- at up to two billion gallons of ethanol per year, impacts on the agricultural sector are mild;
- beyond two billion gallons per year, diversification away from corn appears to be necessary to avoid major feed price inflation;
- farm income rises because of crop-price increases; and
- exports of food grains are affected differently by alternative feedstocks. High-energy sorghum may compete for land with wheat.

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Issued November 1982

An Experimental Investigation into Fast Pyrolysis of Biomass using an Entrained-Flow Reactor

Mark Bohn
Charles Benham

Objective: Describe experiments to determine pyrolysis gas composition resulting from fast pyrolysis of agricultural waste feedstocks and municipal waste.

Discussion: Pyrolysis experiments were conducted using 30- and 90-centimeter entrained-flow reactors, with steam as a carrier gas and two different feedstocks — wheat straw and powdered material derived from municipal solid waste (ECO-II™). Reactor wall temperatures were varied from 700°C (1292°F) to 1400°C (2552°F). Batch experiments were run on wheat straw using a Pyroprobe™. The samples also were heated with the Pyroprobe at a high rate to 1000°C (1832°F) and held at that temperature for a variable time from 0.05 to 4.95 seconds. Gas composition data from tests using ECO-II were comparable to previously reported data, but ethylene yield appeared

to vary with reactor wall temperature and residence time. Olefin yields in the wheat straw tests were about one-half that obtained from ECO-II. The high olefin yields from ECO-II appear to be due to the presence of plastics in the feedstock. In the wheat straw tests with the Pyroprobe for residence times up to 0.15 seconds at 1000°C volume fractions of ethylene, propylene, and methane increased while that of carbon dioxide decreased. Subsequently, only carbon monoxide and hydrogen were produced.

Seven figures are included.

Conclusions: The changing gas composition using the Pyroprobe may be related to poor thermal contact and suggests caution in its use.

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Issued September 1983

Costs for Alternative Grain Residue Collection Systems

Silvio J. Flaim
Bernie Neenan
Jan Dauve
Harry P. Mapp, Jr.

Objective: Determine the market conditions necessary to induce agricultural producers to harvest grain residues.

Discussion: The costs of collecting corn and soybean residues on a "typical" Iowa farm were developed for two collection systems (stacks and large round bales) and for conventional and reduced tillage techniques. Detailed cost breakdowns are presented along with revenues from the sale of the residue at various prices, including a price comparable to that of coal.

Twenty-two tables are included.

Conclusions: Positive net energy production was achieved over the different conditions of tillage and collection. Reduced tillage leads to a lower cost of harvest than conventional tillage, and stacks are cheaper than bales. The dominating effect, in terms of cost of production, is the tillage practice used. The ratio of energy produced to energy consumed in production ranges from 26 for conventional tillage with large round bales of soybeans to 135 for reduced tillage with stacks of corn residue.

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Issued September 1983

SERI High Pressure Molecular Beam Mass End Spectrometric Sampling System

Tom Milne

Objective: Outline the design, objectives, and performance of the custom-designed SERI high pressure, molecular-beam mass spectrometric sampling system.

Discussion: Specialized sampling and mass spectral apparatus is needed to improve understanding at the molecular level of the primary and secondary pyrolysis processes in the conversion of biomass to olefinic gases. Briefly reviewed is the theory of high pressure, molecular-beam mass spectrometric sampling, including a discussion of the principal pheno-

mena that affect results. The hardware and circuits of the sampling and data acquisition system are described. Finally, system performance and capability are reviewed and representative data outputs are presented.

The report includes 17 figures and 2 tables.

Conclusion: The system has lived up to design expectations and appears suitable for carrying out the direct, real-time observation of transient processes in fast pyrolysis.

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Solar Report Summary

Issued September 1983

Survey of the Electrochemistry of Some Biomass-Derived Compounds

Helena L. Chum

Robert A. Osteryoung

Objective: Survey the literature on the electrochemistry of selected biomass-derived compounds to aid evaluations of the electrochemical conversion of biomass-derived compounds into energy-intensive chemicals, petrochemical substitutes, useful chemicals, and electricity.

Discussion: The electrochemical reactions of the selected biomass-derived compounds are reviewed with emphasis on the synthesis of chemical compounds and electric power generation in fuel cells. Only the main polymeric components of biomass, which account for a large proportion, are surveyed. The polymers cellulose, hemicelluloses, starch, and lignin are reviewed, as well as selected monosaccharides and chars of lignins.

Chemicals successfully synthesized electroorganically from mono- and polysaccharides include dialdehyde starch, aldonic acids, and polyalcohols. In general, such syntheses aim at specialty chemicals. Fuel cells employing poly- and monosaccharides generate low power densities in the aqueous solutions investigated (neutral, alkaline, and acid) under 90°C. The research did not fully utilize well-developed technology for fuel cell electrodes and catalysts. Emphasis of the research has been in special applications such as glucose sensors and implantable cardiac pacemakers.

Electrochemical oxidation or reduction research of

lignins of different species and in different media, has emphasized the production of low-molecular-weight carboxyl- and carbonyl-containing compounds as well as of modified lignins with suitable physicochemical properties for polymer applications. Reductive degradation experiments synthesized of monomeric and dimeric phenolic units. Analytical applications of electrochemical techniques are reviewed and applied to lignins. The use of electrochemical delignification in the pulp and paper industry is also briefly covered.

Pyrolysis of lignins produces thermoplastic materials with semiconducting properties. Their possible uses as electrodes or depolarizers are reviewed. Because these chars are analogous to coke materials, review of some of the electrochemistry of direct and indirect fuel cells using coke materials is included.

Sixteen figures and nine tables are included.

Conclusions: The electrochemical production of energy-intensive chemicals or petrochemical substitutes from biomass-derived compounds has not been addressed in the literature. Important is electrochemical research of polymeric materials resulting from newly developed pretreatments of biomass, such as explosive decompression and organosol pretreatments of wood. Because lignins are the only renewable source of phenolic compounds, electrochemical research of these materials is strongly encouraged.

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Solar Report Summary

Issued September 1983

Water Hyacinth Production Primary and Advanced Treatment of Wastewater

Reedy Creek Improvement District
Paul Bergeron, Technical Monitor

Objective: To expand a novel wastewater treatment facility under investigation to permit the production of an energy crop sufficient for the future demonstration of the system's capacity to generate useful energy, in particular to maximize the yields of water hyacinth for conversion to biogas while treating wastewater.

Discussion: A prototype water hyacinth wastewater treatment system has been in operation for two years at Walt Disney World, near Orlando, Florida. Typically, the hyacinth system removes 80%-90% total suspended solids and B.O.D. from the influent stream. Major impacts on water quality exiting the system are: seasonal variations in solar radiation, air, and water temperature; operational problems, particularly harvesting equipment breakdown, and retention time in the ponds. Phosphorus and nitrogen removal show a strong seasonal dependence, with removal rates varying from 0.08 to 1.11 g/m²/day for N and from 0.05 to 0.29 g/m²/day for P.

Nitrogen removal rates show a strong dependence on retention times, with a retention time of 5 days appearing to be a critical limit for the establishment of an active population of denitrifying bacteria. Hyacinth biomass productivity of the system was approximately 66.7 dry metric tons per hectare year (30 dry tons/acre/yr) during the second year of operation. An Experimental Test Unit (ETU) for anaerobic digestion of hyacinths to methane will be installed by late 1983.

Conclusions: Despite numerous problems with system construction and operation, much information has been acquired on system operation and efficiency. With no attempt at system optimization, biomass yields have been as high as 58 dry tons/acre/yr and secondary wastewater treatment standards have been met. The concept appears feasible and should be economically attractive in the near future.

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Solar Report Summary

Issued January 1985

Objective: To present first-season results from studies of stand establishment and management of emergent aquatic plants relating to nutrient requirements, wetland species yield comparison and micropropagation.

Discussion: Emergent aquatic plants such as *Typha* spp. (cattails), *Spartanium* spp. (bur reed), *Phragmites* (reeds), and *Scirpus* spp. (rushes) have been identified as potential biomass crops. The high productivity of these plants coupled with the large amount of land potentially available for emergent aquatic production without competing with traditional agriculture has led to research into methods of emergent aquatics production in managed stands. The ultimate goal is the development of a management system that maximizes sustained yield minimizing costly inputs and environmental degradation.

Nine figures and 17 tables are included.

Emergent Aquatics: Stand Establishment, Management and Species Screening

A Subcontract Report for Solar Energy Research Institute

D. C. Pratt
N. J. Andrews
D. R. Dubbe
E. G. Garver
M. Penko
P. E. Read
E. S. Zimmerman
University of Minnesota
Bio-Energy Coordinating Office

Conclusions: In a comparison of the relative effectiveness of seeds, seedlings, and rhizomes for stand establishment, rhizomes appeared to be more consistent and productive under a wide variety of conditions. Both rhizome-and seedling-established plots grew successfully on excavated peatland sites. First season results from a multiyear fertilizer rate experiment indicate that fertilizer treatment resulted in significantly increased tissue nutrient concentrations which should carry over into subsequent growing seasons. Shoot density and below-ground dry weight were also significantly increased by phosphorus+potassium and potassium applications, respectively. First season yields of selected wetland species from managed paddies generally were comparable to yields reported from natural stands. Several particularly productive clones of *Typha* spp. have been identified. A method of establishing *Typha* in tissue culture is described.

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Solar Report Summary

Issued January 1985

Evaluation of Nondistillation Ethanol Separation Processes

L. Douglas
D. Feinberg
Solar Energy Research Institute

Objective: To compare energy and capital cost requirements with the requirements of distillation systems for several ethanol/water separation processes under past and present SERI-sponsored development. The potential for these processes to replace all or a portion of a distillation system will be assessed.

Discussion: Distillation has been the conventional method of separating ethanol and water. An integrated two- to three-column vapor reuse distillation process requires approximately 18,000 Btu/gal to produce anhydrous alcohol from a 6 wt % feed. This is over 20% of the heating value (84,000 Btu/gal) of the ethanol product. Vacuum distillation without fully integrated heat recovery systems consumes even larger amounts of energy. For a given distillation process, the energy requirement can be reduced by decreasing the external reflux ratio, but the resulting increased tower capacity requires a trade-off between capital and operating costs to minimize total system costs. Several nonconventional separation processes have been investigated for their commercial potential. The Cantrell-Petrek Associates diffusion/carrier gas distillation process uses nitrogen gas at partial pressures sufficiently high that, in principle, no ethanol/water azeotrope is formed. Liquid extraction processes, developed by Intertechnology/Solar/Science Applications, Inc., and Georgia Tech, can offer energy savings since the amount of material that must be vaporized is small. The Intertechnology/Solar/Science

Applications, Inc., process uses a light paraffin oil, while Georgia Tech's two-stage process employs 2-ethyl hexanol (EHOH) followed by ISOPAR-L. Adsorption processes of two distinct types are under consideration. In the Hydrocarbon Research, Inc., process, the ethanol/water mixture is first fed in the liquid phase to activated carbon columns and then to molecular sieves. In the Purdue University process, the mixture is vaporized and then adsorbed on either grain or calcium sulfate. Besides the distillation in the Purdue University process, energy is only required in these processes to regenerate the adsorption beds. Shock Hydrodynamics has formulated a synthetic polymer that selectively absorbs ethanol from ethanol/water mixtures. Southern Research Institute is developing ethanol-selective membranes that will separate liquid ethanol/water mixtures. A private German firm also uses membranes, but their mixtures are fed into the vapor phase into a process called pervaporation.

Process capacities ranged from 8000 gal/yr to 27 million gal/yr; but with processes where the equipment and economics were completely defined, the capacities were about 25 million gal/yr. Input concentration of ethanol to each process must also be specified. If the experimental work and system designs used feed concentrations greater than the 10-15 wt % ethanol (which is commonly available in fermentation beers), an additional factor was added to account for the production of the specified concentration, starting

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from 10%. In some cases, detailed equipment specification and/or cost estimates were unavailable, and it was not reasonable to prepare them from poor data.

Continuing work on some of the processes should alleviate this shortcoming.

Fourteen figures and four tables are included.

Conclusions: Data, some preliminary, show that certain processes have technical and economic potential for displacing all, or portions of, the distillation units in an alcohol plant.

Solar Report Summary

Issued January 1985

Parametric Analysis Support for Alcohol Fuels Process Development

1 January - 30 June 1981
A Subcontract Report for
Solar Energy Research Institute

Chem Systems Inc.
New York, New York

Objective: To determine the effects of pretreatment, delignification, alternate feedstocks and hydrolysis configurations on the selling price of ethanol, using parametric analyses of a 50 million gal/yr high-temperature acid hydrolysis plant.

Discussion: This report describes parametric analyses of an alcohol fuels plant producing 50 million gal/yr of ethanol from corn stover or aspen wood by dilute acid hydrolysis. The analyses were carried out using the simulation model developed by Chem Systems Inc. The model performs material and energy balances, estimates capital and operating costs, and calculates the selling price of ethanol. The simulation models pretreatments such as steam explosion and ethanol solvent delignification prehydrolysis, hydrolysis, fermentation, and ethanol purification. Analyses were carried out to determine the effect of pretreatments, delignification, alternate feedstocks, and hydrolysis configurations.

Eleven-figures and 15 tables are included.

Conclusions: Pretreatment steps were shown to have no benefit in acid hydrolysis, since surface area

and lignin content are not limiting factors in the reaction rates. Solvent delignification with ethanol has no advantage if the lignin has only fuel value. Lignin must have a value greater than \$0.40/lb for steam explosion and delignification to be profitable. Elimination of steam explosion and solvent delignification reduces the selling price of ethanol by 40% compared to the base case (if lignin has only a fuel value) because of the reduction in capital and energy costs. Sensitivity analyses were performed to determine the effect of hydrolysis on yield and selling price. Concentration of the sugar solution prior to fermentation is shown to be undesirable as long as the aqueous stream from the bottom of the distillation tower is sent to the waste pond. An improved case, deleting the pretreatment and delignification steps, was simulated and yielded ethanol at \$2.20/gal and 50 million gal/yr capacity. Finally, computer simulations determined the effect of plant size on the cost of ethanol. This improved system does not yet constitute an optimized system. Significant further cost reductions can be made by increasing the solids content of the processed streams. Large reductions in cost would also result from by-product credits for furfural or lignin produced by less expensive caustic delignification.

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Issued January 1985

Process Design and Economics for Ethanol from Corn Stover via Dilute Acid Hydrolysis

Development of a Base-Case Flowsheet
for Parametric Analysis of Acid
Hydrolysis Processes

A Subcontract Report for
Solar Energy Research Institute

Chem Systems Inc.
New York, New York

Objective: To present a detailed flow sheet (including material and energy balances), capital cost estimate, and economic analysis of a plant producing 50 million gal/yr of ethanol from corn stover. The flow sheet allows identification of important research areas and serves as the basis for a process simulation model.

Discussion: The cellulose-to-ethanol plant process can be divided into six sections: pretreatment, hydrolysis, fermentation, purification, carbon dioxide recovery, and heat generation and waste treatment. In the pretreatment section, the raw corn stover undergoes steam explosion, the lignin is extracted by ethanol extraction, and the amorphous five- and six-carbon sugars removed in prehydrolysis. The crystalline cellulose is hydrolyzed in the hydrolysis reactor. The sugar solution from the prehydrolysis and hydrolysis sections is neutralized and fermented to carbon dioxide and ethanol in a train of continuous fermenters. The

ethanol is recovered by a distillation process, and the carbon dioxide is cleaned and liquified. The unreacted solids and various waste streams are either burned or sent to the waste pond.

Capital and operating costs estimates are developed for the plant.

Six figures and 17 tables are included.

Conclusion: The total plant cost is estimated to be \$236 million. The prime costs are heat generation, pretreatment, and hydrolysis. The ethanol produced costs \$3.60/gal. Elimination of the lignin solvent extraction step and the prefermentation sugar concentration steps are recommended to reduce both the capital investment and energy usage of the plant. The plant design was a nonoptimized first approximation, and as such, does not produce ethanol at a competitive cost. However, it serves as a basis for further optimization and improvement.

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Solar Report Summary

Issued June 1986

Wetland Biomass Production: Emergent Aquatic Management Options and Evaluations

D. C. Pratt
D. R. Dubbe
E. G. Garver
P. J. Linton

Objective: Describe research conducted at the University of Minnesota to identify, test, and evaluate the production practices necessary to capitalize on emergent aquatic plants as potential sources of biomass.

Discussion: Wetlands dominated by *Typha* (cat-tails) and other emergent vegetation, such as *Phragmites* (reeds) and *Scirpus* (rushes), are some of the most productive natural systems in the temperate zone. The high-yield potential and chemical composition of *Typha* make it a particularly viable energy crop. Researchers involved in the Wetland Biomass Production Project, developed at the University of Minnesota, are studying ways to realize the potential of *Typha* as an energy source.

Different wetland species are compared. Site selection and stand establishment are explained. Variation in *Typha* species is presented, and the nutrient

requirements for the program are described. Specifics on weed control and rhizome-harvesting possibilities are also included.

The report includes 11 figures and 17 tables; 2 appendices comprising research methodology; and a bibliography of the biology, ecology, and use of *Typha*.

Conclusions: A total annual biomass yield equivalent to 13 tons/acre is possible in planted stands. The almost constant rate of biomass accumulation of *Typha* is greatest between June 15 and September 15. Following the period of maximum biomass accrual, nutrients and dry weight compounds translocate to the below-ground tissue. Based on the maximum wetland area in Minnesota and the demonstrated yield figures of 9-13 tons/acre, the potential gross energy from *Typha* bioenergy systems could be 1.3-1.8 quads/year.

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Solar Report Summary

Issued June 1986

Thermochemical Pretreatment of Lignocellulosic Biomass for Increasing Anaerobic Biodegradability to Methane

K. Baugh
A. Bachmann
V. L. Beard
J. Levy
P. L. McCarty

Objective: Present the second-year results of a three-year study to determine the feasibility of using heat treatment to increase the anaerobic bioconvertibility of lignocellulosic materials to methane.

Discussion: Anaerobic digestion is a process by which the natural gas supply can be augmented. This process results in the formation of methane by the bacterial decomposition of organic matter in the absence of oxygen. Lignocellulose, the structural material of the cell walls in terrestrial plants, makes up a significant percentage of the organic residuals available. Research into lignocellulosic conversion is being conducted under subcontract to the Solar Energy Research Institute, and the results of the second year of this research are presented.

The publication describes the performance characteristics of the anaerobic baffled reactor (ABR) (a new method of methane fermentation developed in the study) as well as a mathematical model of the factors that affect the rate of waste utilization within the reactor. Lignocellulosic hydrolysis and decomposition are detailed, and the research on lignocellulose and the experimental procedures involved are described. The decomposition of glucose, other monosaccharides, and furfural under autohydrolysis

conditions is also presented, along with an evaluation of the autohydrolysis model. The results of the autohydrolysis rate studies are included. The pretreatment and methane fermentation of white fir slurry and its results are described.

The report contains 6 appendices that detail chemical information, experimental data, regression techniques, and a staged autohydrolysis model; 26 tables and 45 figures accompany the text.

Conclusions: Researchers found that the ABR was capable of loading rates up to 30 kg COD/m³ day (chemical oxygen demand per cubic meter per day) for dilute organic solutions, and that the ABR proved to be simple, easy to operate, and reliable. In studies of temperature and pH effects on lignocellulosic pretreatment, a pH between 2 and 2.5 was found optimum for cellulose hydrolysis, resulting in minimum acid or base decomposition of the sugars formed. In a bench-scale study of the overall heat pretreatment/methane-fermentation system, the staged pretreatment of white fir under optimum conditions resulted in 58% conversion of the carbohydrate heat content and 35% conversion of overall white fir heat content into methane gas.

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Solar Report Summary

Issued June 1986

Objective: Present the results of research conducted at the University of Hawaii to determine whether microalgae can be grown successfully in a shallow outdoor flume without temperature control, the yields of such a system, and the economic and energy-related merits of such mass culture production.

Discussion: Microalgae are attractive as biomass producers because they generally exhibit higher yields and photosynthetic efficiencies than terrestrial plants. Additionally, many species of microalgae produce high concentrations of intracellular oil as energy storage compounds.

The report presents a brief historical and theoretical background in microalgal research and describes the materials and methods involved in the studies, detailing the culture system itself and the analytical data used.

A microalgal species that can be grown in the system on a 12-month basis without temperature control was identified. This strain of *Platymonas* sp. grows rapidly at temperatures from 20° to 34°C, and at salinities from 15 to 35 ppt; neither the lower temperature limit nor the lower salinity limit of the strain was

Research and Development of Shallow Algal Mass Culture Systems for the Production of Oils

Edward A. Laws

determined. Through factorial experiments, the optimum pH was determined to be about 7.5, the optimum culture depth 10 cm, and the optimum flow rate about 30 cm/s. Diluting the culture every third day greatly enhanced production. In this dilution mode, daily yields averaged 46 g/m² ash-free dry weight (AFDW) over a one-month period, which is over two times greater than the best long-term yields achieved in other microalgal mass culture systems grown exclusively on inorganic nutrients. Photosynthetic efficiencies averaged 11% (based on visible light energy).

Thirteen tables and 11 figures accompany the text. An appendix containing analytical data is presented as well.

Conclusions: If photosynthetic efficiencies of 11% can be maintained, then energy from algal biomass will become cost competitive with crude oil as crude oil prices increase. The major cost components for the system described are the energy required to operate the airlift pumps, the energy required to provide fixed nitrogen, and the energy required to harvest and process. If the entire energy content of the microalgae is used, the energy output of the system is over four times greater than the energy input.

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Solar Report Summary

Issued June 1986

Objective: Present the research accomplishments of the Solar Energy Research Institute (SERI) Aquatic Species Program for Fiscal Year 1984.

Discussion: The purpose of the Aquatic Species Program is to improve the productivity, conversion to fuels, and cost-efficiency of aquatic plant culture technologies. The emphasis of the program is on developing a mass culture technology to cultivate oil-yielding microalgae.

The report reviews the activities of this program through 1984. Biological research, engineering research, and technology analysis were conducted, and their results are presented. Biological research focused on screening for productive species, developing culture and management techniques to grow desirable species, and understanding photosynthetic and lipid physiology as it applies to increasing yields. Engineering research centered on the development and analysis of applicable harvesting methods to support technology development through the determination of cost goals, assessment of resources, and evaluation of emerging technologies.

The report includes 19 tables and 36 figures.

Conclusions: Notable results for 1984 are:

- Out of the 320 strains of microalgae that were isolated, 46 were classified as good growers.

SERI Aquatic Species Program 1984 Annual Report

Solar Energy Research Institute

- A screening technique was established that efficiently selects strains that do well in outdoor mass culture.
- Five strains of microalgae that accumulate over 40% lipids were identified.
- Outdoor yields were improved 40% by growing thermophilic strains and developing better management techniques.
- Lipid yield was found to be highest for 3 to 5 days after the onset of nitrogen starvation in green microalgae.
- Cells of *Phaeodactylum tricornutum* preconditioned at low light intensity require less rapid light modulations for photosynthetic efficiency enhancement than cells preconditioned at high light intensity.
- Designs were commissioned for an advanced pond system, an advanced raceway system, and a closed continuous system.
- A technical and economic evaluation indicated that large-scale microalgae production for fuels is feasible, providing that lipid yields from microalgae can be improved, that there is sufficient saline water for large-scale development, and that microalgal lipids can be converted to conventional fluids.

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Solar Report Summary

Issued December 1986

Acid Hydrolysis Experimental Facility Results with Corn Stover

J. W. Barrier
J. D. Broder
R. O. Lambert
G. E. Farina
G. R. Lightsey

Objective: Present the design of the Tennessee Valley Authority (TVA) experimental acid hydrolysis plant in Muscle Shoals, Alabama, along with initial process testing data and research results.

Discussion: Ethanol, which can be produced from agricultural cellulosic materials, has potential for use as a premium liquid fuel to supplement or replace other premium petroleum supplies and as an octane enhancer to replace lead additives in gasoline. TVA, with support from the U.S. Department of Energy, is developing acid hydrolysis technology for converting agricultural cellulosic materials to sugars for fuel-ethanol production in a 4-ton/day experimental plant. The facility allows the use of relatively inexpensive materials and conventional process equipment to minimize capital cost and simplify scale-up to commercial capacity.

Initial tests were performed to verify equipment performance and material-handling capabilities. Two complete experimental runs to evaluate all process steps were conducted in November 1984 and March

1985. The report describes the acid hydrolysis process in detail and also presents the results of experimental plant runs.

One figure is included in the text.

Conclusions: Initial results of acid hydrolysis process development indicate conversion efficiencies exceeding 90% for both hemicellulose and cellulose components of corn-stover foodstock.

Other project achievements include:

- Verification of laboratory and bench research results in the plant-scale experimental facility.
- Enumeration of more research requirements to improve the technology for commercial acceptance.
- Demonstration of inexpensive construction materials in acid hydrolysis process systems.

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Solar Report Summary

Issued December 1986

Objective: Present the results of studies of catalytic mechanisms in biomass gasification.

Discussion: The Pacific Northwest Laboratory (PNL) has developed a catalytic steam-gasification process that converts wood to specific product gases. The goal of PNL's catalytic biomass-gasification program is to maximize the production of specific gas products through the use of catalysts.

Two types of catalysts are involved in these studies: (1) primary catalysts, or generally alkali carbonates, which are doped on or mixed with the biomass in carbon/steam reactions, and (2) secondary catalysts (nickel or other transition metals on supports such as alumina or silica-alumina) used to catalyze secondary gas-phase reactions such as the steam-reforming, methanation, and water-gas shift reaction. Experiments with these catalysts were conducted in a 5-cm diameter, continuous-wood-feed, fixed-catalyst bed reactor.

The behavior of primary catalysts in carbon/steam reactions is presented, as well as the effects of primary catalysts on pyrolysis and other reactions. Catalyst recovery from residue is also described.

The role of secondary catalysts in the production of specific gases is detailed. Active catalyst lifetime and

Catalysis in Biomass Gasification

E. G. Baker
L. K. Mudge

deactivation studies are presented as well. Possible causes of catalyst-activity loss are explained, as are the performances of various catalysts in the tests. Attrition, or physical breakdown, of catalysts is also investigated.

Mechanistic studies of catalytic gasification were also performed to determine the overall effect of alkali carbonates on pyrolysis/gasification and the causes of coking on secondary catalysts. Results of these studies are included.

Two appendices accompany the text, dealing with gas-phase reactor studies with secondary catalysts and data from fixed-bed laboratory tests. Eleven figures and twenty-four tables are also included.

Conclusions: Primary catalysts influenced wood pyrolysis as well as the char/steam reaction. Secondary catalysts were highly effective for converting biomass gasification products to such other products as synthesis gases and methane-rich gas. Nickel catalysts were found most effective among secondary catalysts, but they poisoned rapidly because of catalyst coking (carbon deposition).

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Solar Report Summary

Issued December 1986

Energy from Biomass: Building on a Generic Technology Base Proceedings of the Third Technical Review Meeting

Argonne National Laboratory

Objective: Present the technical papers of the third Technical Review Meeting, held in conjunction with the Southeastern Industrial Biomass Energy Exposition held on November 27-29, 1984 in Atlanta, Georgia.

Discussion: Significant developments have occurred in the biomass energy field in the past decade, and progress continues as a result of projects funded by the U.S. Department of Energy, other governmental agencies, and the private sector. This conference was held to communicate results, capabilities, and needs to researchers, producers of biomass, and users of biomass energy.

The report consists of a compilation of 28 technical papers concerning the following general areas of interest: case studies and economics; technology transfer and resource assessment; methods of productivity and efficiency improvements; financial, legal, institutional, and environmental issues; and advanced concepts and research results. A list of participants in the conference is also included.

The number of tables and figures varies with individual reports.

Conclusions: Conclusions vary with each paper.

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Solar Report Summary

Issued December 1986

Objectives: Present information on recent developments and concepts in the technology of harvesting wood for use as an energy feedstock.

Discussion: Current forest inventories, along with innovative means of increasing the wood energy resource base, have the potential to provide a significant portion of the nation's energy requirements. Recovery of these resources is an important factor in realizing this potential.

The report presents information on a variety of prototype machines designed to harvest trees from existing forests, as well as short-rotation intensively cultured plantations. These machines include swathe cutters and mobile harvesters, residue-recovery equipment, short-rotation harvesters, and steep-slope harvesters. Conventional forest-harvesting equipment is described in a generic sense, and the costs of harvesting and using wood for energy are examined.

Thirty-one figures and seven tables are included in the publication.

Energy Wood Harvesting Technology — A Review-of- the-State-of the Art

Meridian Corporation

Conclusions: The following conclusions are presented:

- The cost of producing energy chips, from stump to point of use, using modified conventional systems, can be expected to range from about \$11-\$23 per green ton.
- Harvesting costs alone account for at least half the total cost. Transportation is also a significant factor.
- The prototype machines are capable of producing energy wood at costs comparable to conventional systems.
- Cost comparison indicates that wood is currently competitive as a replacement for fuel oils or natural gas but may be somewhat less than competitive with coal.

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Solar Report Summary

Issued December 1986

Integrated Fuel Alcohol Production Systems, Phase III, Experimental Facility, Design Report

J. W. Barrier
P. C. Badger
J. D. Broder
G. E. Farina
M. R. Moore
M. F. Forsythe

Objective: To design and specify equipment for an experimental facility to convert crop residues to fermentable sugars and integrate the facility with the existing fermentation and distillation facility.

Discussion: The technology for producing fuel-grade ethanol from agricultural cellulosic materials is being developed by Tennessee Valley Authority (TVA) engineers in Muscle Shoals, Alabama. To this end, their efforts are focused on the design, construction, and operation of a 10-gal/hour experimental facility. Evaluations performed using this large-scale research unit will provide the basis for commercial application of the technology.

The report describes the development of the processes used in the acid hydrolysis plant, as well as the

specifics of the design of the facility itself. A detailed presentation of the equipment and materials necessary for the construction of the plant and future plans for the facility are described also.

The report contains 21 tables and 25 figures. Three appendices are included, consisting of a compilation of manufacturers' literature for major equipment, process-development studies, and the laboratory data for those studies.

Conclusions: Costs cited for building the experimental facility must be used with caution.

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Solar Report Summary

Issued December 1986

Objective: Present estimates of the total amount of woody biomass within the southeastern region of the United States, as well as estimates for the annual growth, removal, and net change of the biomass of growing stock trees and the biomass potentially available for energy each year.

Discussion: The states included are Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia. Woody biomass is the predominant biomass resource in the area. In late 1983 the U.S. Department of Energy established regional biomass energy programs to promote the development of effective uses of biomass for energy on a regional basis. Woody biomass energy potential is derived from logging residues, cull trees, and surplus growth of trees from the commercial forest lands in the 13-state area.

The report describes the methods and analysis used in evaluating the woody biomass of the southeastern region. For both methods and analysis, the area

Woody Biomass Analysis for 13 Southeastern States

Thomas A. Waldrop
Robert T. Brooks, Jr.

characteristics are presented, as is a biomass inventory which includes estimations of specific biomass types. Annual growth, removal, and net change of growing stock are also reviewed, along with estimations of potential annual wood for energy for specific biomass types.

Six appendices are included in the report, consisting of a glossary, distribution maps, and tabular representations of the biomass information by geographic unit. Twenty-four tables and thirty-three figures accompany the text.

Conclusions: The biomass inventory for the entire region is approximately 13.9 billion green tons or 67.5 tons/acre of commercial forestland. Annual biomass growth of growing stock exceeds removals by 161 million green tons or 0.8 ton/acre. Potential annual wood for energy totals 246 million tons or 1.2 tons/acre, which represents an energy source of approximately 2 quads.

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Solar Report Summary

Issued April 1989

Objective: Review the present status of research, determine the highest potential uses of fuel from microalgae, and define the needed technological and financial barriers to cost-effective energy production from microalgae.

Discussion: The study reviews the basic requirements for the production of fuels from microalgae including the needs for light, water, special climate conditions and the fuel product alternatives that are available. From this review of the fundamental physical requirements, the economic evaluation of the various needed components can be completed.

The production of lipid-rich microalgae requires the growth of the organism in shallow salt water ponds with the addition of carbon dioxide and nitrogen. The small organisms must then be harvested, i.e., their water content substantially reduced to allow for further processing. All of these steps are defined and the areas of uncertainty discussed in this document.

Once past the basic production of microalgae, the economic decisions of plant operation, conversion, transportation, and availability of necessary resources are evaluated. The report provides a sensitivity

Fuels from Microalgae: Technology Status, Potential, and Research Requirements

B. Neenan
D. Feinberg
A. Hill
R. McIntosh
K. Terry

analysis of the most important parameters in the entire process. This analysis, in turn, provides a set of economic and technical constraints and requirements for the economical production of fuels.

The report includes 39 figures and 35 tables. An appendix provides the computer program that was used to simulate the operation and economics of microalgal mass culture systems.

Conclusions: Gasoline-type fuels can be produced from microalgae for \$1.60-\$2.00 per gallon by the year 2010 (1984\$) if an aggressive research on production is established. Major improvements need to be made in the biological productivity. Present photosynthetic efficiency must be raised to about 16% in order to be cost-effective. Other biological characteristics must also be enhanced, especially resistance to changes in the salinity of the water.

Other areas that will require additional research include harvesting techniques, availability of saline water and inexpensive carbon dioxide, the conservation of the water and CO₂, and the range of processes for conversion of microalgae to fuel products.

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Ocean Energy

Oceans, covering 70 percent of the Earth's surface, are tremendous natural storehouses of solar energy. Ocean energy resources include tides, waves, currents, salinity gradients, and thermal gradients. The thermal gradients—temperature differences between warm surface waters and cold deeper waters—are caused by the natural storage of solar energy in surface layers of the ocean.

Ocean Thermal Energy Conversion (OTEC) systems use these thermal gradients to produce useful energy. A working fluid such as ammonia is cycled through a mechanical system that exposes it in sequence to warm and then cold water. The warm surface waters vaporize the fluid which is pressurized and expanded through a turbine to produce electricity. This vapor is then condensed using water brought to the system through a long pipe that reaches into the colder regions of the ocean. This liquid is pumped back to the warm surface to begin the work cycle again. In an open cycle version this process can be accomplished using the seawater itself as the working fluid, eliminating the need for pressurized ammonia heat exchangers and creating the possibility for fresh water production.

Unlike most other solar technologies, OTEC can supply energy around the clock, not just when the sun is shining. But the oceanic temperature differences needed to power these systems only exist in the tropical and semi-tropical oceans.

Another method of using the oceans for energy generation is by harnessing ocean waves and ocean currents. There are many possible ways to do this. One of these, called an oscillating water column, utilizes the action of waves to compress air which is then expanded through an air turbine to produce power.

The energy potential of salinity gradients is also being studied. Whenever two solutions—in the case of the ocean, salt and water—of different concentrations exist, there also exists an energy potential between them. The key element is a semi-permeable membrane that separates the two solutions. In one scheme, fresh water will migrate through the membrane into the more salty solution. This increases the pressure in that side of the membrane. The pressure and the water flow associated with this migration across the membrane can drive a generator to produce electricity.



Ocean Energy

SERI Report Summary

Selected Legal and Institutional Issues Related to Ocean Thermal Energy Conversion (OTEC) Development

Ved P. Nanda

Objective: Identify and analyze the legal issues that must be addressed to resolve uncertainties related to OTEC development.

Discussion: Jurisdictional, regulatory, and environmental issues raised by OTEC development are discussed.

In the jurisdictional area, the primary issues are discussed in two contexts: national-international and federal-state. Regulatory issues are discussed in terms of international and federal-state contexts. The environmental issues center on possible toxic effects on biota, adverse effects of changing salinity and thermal gradients in seawater, the safety of workers, and the effect on the microclimate caused by slightly lower temperatures around the OTEC plant.

Conclusions:

- The United States should accept the 200-mile

coastal state competence relating to OTEC siting and deployment.

- Congress should enact legislation creating a 200-mile Coastal Energy Conservation and Management Zone.
- An efficient management system should be devised for the 200-mile marine zone.
- Imaginative bilateral and regional arrangements should be created.
- It is desirable to establish an OTEC regulatory mechanism administered by the federal government.
- The drafting of international conventions and a code of conduct dealing with OTEC should be considered as high priority tasks.

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Solar Report Summary

Issued September 1983

The Exergy of the Ocean Thermal Resource and the Second-Law Efficiency of Idealized Ocean Thermal Energy Conversion Power Cycles

D. H. Johnson

Objectives: First, to develop a formula to compute the maximum amount of work which can be extracted from a given combined mass of hot and cold ocean water (this quantity is called the exergy of the ocean thermal resource); and second, to compare the second-law efficiencies of various ocean thermal energy conversion (OTEC) power cycles.

Discussion: In an OTEC plant a finite mass of warm surface water acts as a source of energy as it is pumped through a heat exchanger, and a finite mass of cold water pumped from the deep ocean acts as a sink. The temperatures of the source and the sink of energy for an OTEC plant change as a result of heat transfer during the OTEC power cycle. This fact is shown to be of critical importance in calculating the exergy of the ocean thermal resource.

The second-law efficiencies of the multicomponent working-fluid cycle, the Beck cycle, and the open and closed single-and multiple-stage Rankine cycles are compared in this report. These types of OTEC power plants are analyzed assuming that all deviations from a plant which makes use of all the exergy occur because of irreversible transfer of heat across a finite

temperature difference. Conversion of thermal energy to other forms is assumed to occur reversibly.

Ten figures and one table are included. An appendix considers heat losses in OTEC inlet and outlet pipes.

Conclusions: The exergy depends on the quantity $(T_w - T_c)^2$, where T_w is the temperature of the warm surface water and T_c is the temperature of cold deep water. The comparison of second-law efficiencies of various OTEC power cycles shows that the multistage Rankine open cycle with just three stages has the potential of best using the exergy of the ocean thermal resource. This is followed in order of decreasing second-law efficiency by the multicomponent working fluid cycle, the Beck cycle, the Rankine single-stage open cycle, the multi-stage closed cycle with three stages, and the Rankine single-stage closed cycle.

The exergy, not the temperature difference, should be used to characterize the ocean thermal resource, and the advantages of staging open cycle OTEC plants should be seriously considered.

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Solar Report Summary

Issued September 1983

Performance and Stability of the Mist Lift Process for Open-Cycle OTEC

Roger L. Davenport

Objective: Develop an analytical understanding of the mist lift process to allow decisions about the process viability for ocean thermal energy conversion (OTEC).

Discussion: This report presents the results of SERI's analytical studies of the mist lift process. Using a single drop-size steady-state model of the mist-lift process, parametric studies of the performance and design sensitivity of the mist flow were developed. Two new models were developed. One model improves on the previously developed multiple drop-size model by including collision-induced breakup of drops in the mist. The other model predicts the transient response of the mist flow to perturbations in the injector and condenser conditions. Results from the two new models are presented and discussed.

Twenty-five figures and five tables are included. In Appendix A, the mist lift equations are developed.

Listings of the computer programs used in the study are included in Appendix B.

Conclusions: Drops tend to grow rapidly to a mean diameter of about 0.5 millimeter and collisions prevent the drops from growing much larger than a few millimeters. Lift is best accomplished while the drops are small. Thus, temperature flashdown at the injector must be adequate to produce sufficient vapor to lift the drops at the beginning of the lift process, before the drops begin to grow.

The parametric studies performed using the single drop-size model indicate that the mist-lift process will perform under a variety of conditions. Results of the transient mist-lift model indicate that the mist flow process is stable to perturbations in the operating conditions, as long as the conditions remain within the steady-state operational envelope for the particular mist-lift tube under study.

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Solar Report Summary

Issued January 1985

A Reference Guide to Fabrication Details and Preliminary Testing of a Pneumatic Wave Energy Converter

Thermal Research Branch
Custom Engineering, Inc.
Solar Energy Research Institute

Objective: To describe the subsystems of a pneumatic wave energy converter (PWEC), and document shakedown tests of the PWEC; and to provide a reference on some of the precautions and maintenance requirements needed to prevent catastrophic system failures.

Discussion: In February, 1980, SERI accepted responsibility from the U.S. Department of Energy to complete the fabrication and assembly of a 125-kilowatt PWEC. Upon completion, the PWEC was tested to ensure that all systems were functioning as designed.

Following a brief introduction, the total PWEC system is described in detail. Detailed presentations of the individual subsystems, maintenance requirements, and operational and safety aspects of the systems are presented. The fabrication and testing of the PWEC are recounted, and test results are discussed.

Eight figures and five tables are included. Two appendices include an index of drawings for the system, and an equipment documentation table.

Conclusions:

- A 125-kW_e pneumatic wave energy converter has been fabricated with all mechanical and electrical systems functionally checked.
- Specific recommendations on operating and setup procedures are identified along with references including complete design drawing lists and operating manuals.
- Instrumentation installed for the prospect of future aerodynamic performance testing is described in detail.
- Maintenance requirements to prevent mechanical and electrical failure are outlined.
- No-load running torque and coast-down tests on the gearbox/turbine and generator quantified the moment of inertias required for dynamic simulation models.
- Special operating "warnings" on equipment that can cause excessive device damage or endanger the safety of people working around this prototype device are highlighted.

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Passive Solar Heating & Cooling

Passive solar buildings are intended to collect, store and distribute the sun's heat with little or no mechanical power. This is accomplished through design techniques and proper site orientation. Ideally, a passive solar building is positioned with broadsides facing south (and north) so the walls and roof receive maximum solar radiation in the winter and minimum in summer. The long axis of a typical building should run east and west to allow a southerly exposure of most of the structure. On the south side there should be large, well insulated windows or walls with a high thermal mass to capture the sun's heat. Windows on the north side should be kept to a minimum in order to maximize solar heat gain in the winter when the sun is lower in the sky.

Three basic classifications are used to describe passive designs: *direct*, *indirect* and *isolated*. The simplest passive system is the direct heating design in which sunlight shines directly into the living area through south-facing windows. The heat is stored in floors and walls of high thermal mass and radiated

into living or working space at night when it is most needed.

Indirect systems capture and store the sun's heat before it enters the living area. Thermal storage walls made of high-density materials, such as masonry or water, are placed on the south side of the building where they collect and store the sun's heat which can be released into living areas by radiation, convection or conduction.

Isolated heating systems collect and store heat in an area set apart from the living space. Since the living area is not directly exposed to the sun, the amount of heat it receives can be more closely controlled than with other passive approaches.

In all systems, site and landscaping are important considerations. Most passive homes will need a back-up source for heating and cooling, but properly designed passive systems can provide from 40 percent to 80 percent of a building's heating and cooling needs.

SERI Report Summary

Low Cost Performance Evaluation of Passive Solar Buildings

Larry S. Palmiter
L. Blair Hamilton
Michael J. Holtz

Objective: Investigate low-cost, low-level monitoring approaches to thermal performance evaluation of passive solar buildings.

Discussion: The current status of low-cost performance evaluation was assessed by means of a literature search, examination of low-cost thermal performance evaluation techniques already proposed, and a series of working meetings attended by researchers in performance evaluation of passive solar buildings. Using this information, recommendations were made for techniques and equipment to be used.

The method proposed in the report is not applicable for all buildings. It works best with small residential and commercial buildings in cold climates. Only space heating is addressed. Buildings that use solid fuels as an auxiliary energy source are not considered.

Seven tables and one figure are included.

Conclusions: Twenty-two performance factors, in-

cluding overall building performance, can be calculated using the following data:

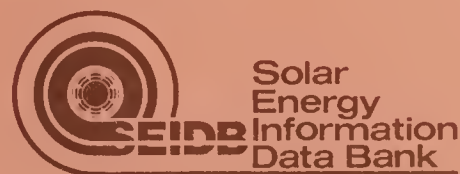
- incident solar radiation on horizontal,
- incident solar radiation on collector,
- outdoor dry-bulb temperature,
- indoor space dry-bulb temperature, power to electric heating auxiliary or furnace burner operating time,
- electric power to lights and appliances,
- movable insulation operating time
- vent opening, and
- solar operating energy.

Recommended instrumentation and data processing specifications are detailed in the last section of the report.

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SERI Report Summary

A Simple Design Tool for Sizing Solar Ponds

Michael Edesess
Jon Henderson
T. S. Jayadev

Objective: Present simple formulas in "cookbook" form for sizing solar ponds.

Discussion: After a brief introduction to the concept of solar ponds, the report describes a base case salt gradient solar pond design and a series of simple steps to determine the surface area and depth for a pond of that design (Section 2). Next, the authors present an example of a model including the results of a full-scale computer simulation (Section 3). In Section 4, the method is used to obtain estimated pond sizes for various locations in the United States (using only the base case salt gradient pond design). The report then outlines the method for more general solar pond designs, ranging from salt gradient to saltless ponds (Section 5). Section 6 examines the origins of errors in the sim-

ple method presented. In Section 7, the method is inverted by showing how to estimate output temperatures for a pond of a particular size and shape. The report also describes how to obtain the demand served when output temperatures are specified. Finally, in Section 8, hints are given on applying the method to an actual sizing problem.

The accompanying appendix presents the theoretical derivation of the simple method. Three figures and five tables complement the text.

Conclusions: The simple formulas given in the report will enable a potential user to determine the approximate size solar pond needed for a particular application and location.

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SERI Report Summary

Issued June 1981

Reduction and Publication of Passive Solar Data: A Proposed Data Format Final Report

Robert D. Busch

Objective: Identify a set of key variables for performance of passive solar systems and present a proposed standard format for publication of those data.

Discussion: A list of important variables is discussed, which represents the minimum information necessary to validate simulation models and to calculate performance parameters for passive solar systems. This variable list was compiled through interviews with simulation code developers and a review of papers on the performance of passive structures. A standard-data format is proposed for the publication of data. This format was created through discussions with agencies involved in passive solar systems and is similar to a format proposed to the International Energy Agency by the Swedish Royal Institute of Technology.

Three tables and three figures complement the text. The list of key variables is presented in Table I, the proposed data format in Table II, and generic types of passive solar system data in Table III. Three appendices give detailed background information used in creation of the key variable set and the proposed format.

Conclusions: Key data in standard format will be highly valuable to solar simulation model developers and to those doing passive solar research. Performance data from eight passive homes or test rooms are presented in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Performance Data for Passive Systems The Los Alamos Scientific Laboratory Test Rooms

Bickle/CM Inc.

Objective: Present, in a standard format, passive solar system performance data from test rooms at Los Alamos Scientific Laboratory (LASL), for the purpose of passive simulation code validation.

Discussion: Performance data are presented in standard format for a direct gain cell and for a Trombe Wall cell constructed at LASL. In each case, the surrounding environment (Los Alamos, N.M.), the construction of the cell, and the data acquisition system are described in detail. The

data are presented in both graph and tabular form.

Conclusion: The reported data should be valuable to passive solar system designers and to simulation code developers. Standard-format data from seven other sites are presented in companion reports (SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Performance Data for Passive Systems The National Center for Appropriate Technology Test Rooms

Bickle/CM Inc.

Objective: Present, in a standard format, passive solar system performance data from test facilities at the National Center for Appropriate Technology, for the purpose of passive simulation code validation.

Discussion: Performance data are presented in standard format for a direct gain cell and for a Trombe Wall cell constructed at the National Center for Appropriate Technology. For each case, the surrounding environment (Butte, Mont.), the construction of the cell, and the data acquisi-

tion system are described in detail. The data are presented in both graph and tabular form.

Conclusions: The reported data should be valuable to passive system designers and to simulation code developers. Data from seven other sites are presented in companion reports (SERI/TR-0924-2, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Passive Solar Data From the Balcomb House Reduction and Publication of Passive Solar Data

Bickle/CM Inc.

Objective: Present, in a standard format, performance data for the Balcomb house, a passive solar structure near Santa Fe, N.M., for the purpose of passive simulation code validation.

Discussion: The Balcomb house uses direct insolation and a mass storage wall for heating. Data were taken during actual occupancy of the house. The surrounding environment, the construction of the house, the construction of the passive system, and the data acquisition system are described in detail. The data are presented in both graph and

tabular form.

Detailed house plans are included in the report.

Conclusions: The reported data should be valuable to passive system designers and to developers of simulation models. Standard-format data from seven other sites are included in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Performance Data for Passive Systems The Ralph Williamson House

Bickle/CM Inc.

Objective: Present, in a standard-format, performance data for the Ralph Williamson house, a passive solar structure near Sante Fe, N.M., for the purpose of passive simulation code validation.

Discussion: The Williamson house depends upon direct access of sunlight and thermal storage mass in its walls for passive solar heating. Data were taken during actual occupancy of the house and are presented in standard format. The surrounding environment, the construction of the house, and the data acquisition system are discussed in detail. Plans and photographs of the house are included

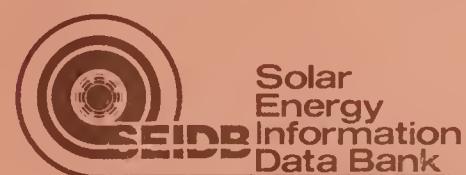
in Appendix A. Appendix B shows the locations of the temperature sensors in the house. The resulting data are presented in both graph and tabular form.

Conclusions: The reported data should be valuable to passive system designers and to developers of solar simulation models. Data from seven other sites are presented in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Performance Data for Passive Systems The Bruce Hunn House

Bickle/CM Inc.

Objective: Present, in a standard format, performance data for the Bruce Hunn house, a passive solar structure in White Rock, N.M., for the purpose of passive simulation code validation.

Discussion: The Hunn house depends upon a Trombe Wall design for its heating. The house was extensively instrumented by Los Alamos Scientific Laboratory, and performance data were taken during initial occupancy of the house. Details of the surrounding environment, the construction of the house, and the data acquisition system are included in the report. The data are presented in both graph and tabular form. Appendix A gives

detailed cross-section plans of the walls, roof, and floor of the house. Appendix B includes photographs and plans of the house. Appendix C is a graph of the electricity and gas consumption of the house.

Conclusions: The reported data should be valuable to passive system designers and to solar simulation model developers. Data from seven other sites are presented in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-7, SERI/TR-0924-8, SERI/TR-0924-9).

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Performance Data for Passive Systems The University of Nebraska Test Rooms

Bickle/CM Inc.

Objective: Present, in a standard format, performance data for direct gain and Trombe Wall test rooms at the University of Nebraska, in Omaha, for the purpose of passive simulation code validation.

Discussion: A series of test rooms was built at the University of Nebraska to determine the technical and economical feasibility of passive solar heating and cooling techniques in the Midwestern United States. Data were collected for both direct gain and Trombe Wall configurations. The report describes in detail the surrounding environment and weather, the construction of the test facilities,

the passive solar systems, and the data acquisition system. The data are presented both in graph and tabular form. Construction plans for the test modules are included in Appendix A.

Conclusions: The reported data should be valuable to passive system designers and to developers of solar simulation models. Data from seven other sites are included in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-8, SERI/TR-0924-9).

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SERI Report Summary

Issued June 1981

Performance Data for Passive Systems The Charless Fowlkes House

Bickle/CM Inc.

Objective: Present, in a standard format, performance data for the Charless Fowlkes house, a passive solar structure in Bozeman, Mont., for the purpose of passive simulation code validation.

Discussion: The Fowlkes house uses a water tube storage wall for its passive solar heating system. The performance of the system has been monitored during occupancy of the house. The house was constructed under a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. The report describes in detail the local environment, the house itself, and the computerized data acquisition system. The perform-

ance data are presented in both graph and tabular form. Appendix A gives detailed cross-section plans of the walls, roof, and floor. Appendix B shows photographs and plans of the house construction. Appendix C is a plan showing locations of the sensors used to collect the data.

Conclusions: The reported data should be valuable for passive system designers and to solar simulation model developers. Performance data from seven other sites are presented in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-9).

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Issued June 1981

Performance Data for Passive Systems The Maeda/Nittler Suncatcher House

Bickle/CM Inc.

Objective: Present, in a standard format, performance data for the Maeda/Nittler house, a passive solar structure in Davis, Calif., for the purpose of passive simulation code validation.

Discussion: The Suncatcher passive solar design uses direct gain and mass storage of solar heat. The house was built and has been monitored by Davis Alternative Technology Associates. The local environment and weather, the house, the passive solar system, and the computerized data acquisition system are discussed in detail. The performance data are presented in both graph and tabular form. Appendix A gives weather and utility

usage records for the life of the house. Appendix B shows plans of the house. Appendix C presents photographs and plans of the details of the solar heating system.

Conclusions: The reported data should be valuable to passive system designers and to solar simulation code developers. Performance data from seven other sites are given in companion reports (SERI/TR-0924-2, SERI/TR-0924-3, SERI/TR-0924-4, SERI/TR-0924-5, SERI/TR-0924-6, SERI/TR-0924-7, SERI/TR-0924-8).

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SERI Report Summary

Issued June 1981

Human Comfort and Auxiliary Control Considerations in Passive Solar Structures

W. Place
R. Kammerud
B. Andersson
B. Curtis
W. Carroll
C. Christensen
M. Hannifan

Objective: Investigate energy consumption and human comfort implications of various passive solar and energy-conservation strategies for single-family, slab-on-grade residences in Albuquerque, N.M., and in Washington, D.C.

Discussion: The building energy analysis computer program BLAST (Building Loads Analysis and System Thermodynamics) was used to perform annual dynamic heating and cooling load calculations for a building in which the glazing area, glazing location, and thermal mass were varied systematically. The impacts on building performance of forced-flow ventilative cooling and nighttime and weekday thermostat setting were investigated.

BLAST calculates the air temperature (T_a) and mean radiant temperature (T_{mr}) in each zone for every hour of the year; a weighted average of T_a and T_{mr} was used to evaluate comfort conditions under various circumstances.

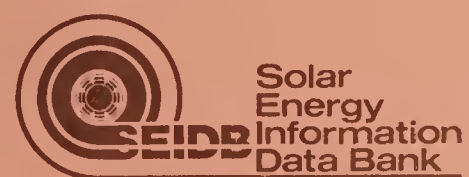
Nine figures and one table are included in the report.

Conclusions: The results indicate that the annual heating and cooling loads are highly sensitive to glazing area, glazing location, and thermostatic controls. Annual cooling loads are substantially reduced by increased thermal mass in the walls. In contrast, annual heating loads are fairly insensitive to increased thermal mass in the walls, unless large areas of south glazing are involved.

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Solar Report Summary

Issued November 1982

A Frequency-Domain Approach to Passive Building Energy Analysis

Krishnappa Subbarao
John Anderson

Objective: Present a new graphical approach to passive building design.

Discussion: The admittances of each building element to the major driving functions (principally, outdoor temperature and solar radiation) are represented in the form of two-dimensional vectors, and the overall dynamic response of the building is obtained by vector addition. The interaction among components is shown to be naturally accounted for by a modification of the admittance of a component. Emphasis is placed on diagrammatic vector addition to quickly give the user an idea of the relative size of the dynamic contribution made by each component of the building. This is analogous to the addition of the steady-state heat-loss coefficients through various elements of a building to form the overall heat-loss coefficient. From the results of this addition and from a simple analysis of the weather, one can easily obtain (1) the elevation of the average indoor temperature above the average outdoor temperature, and (2) the amplitude and phase of the diurnal (or any other frequency)

fluctuation of the indoor air temperature. The former is a measure of the actual solar gain that reaches the indoor air, and the latter describes the various thermal masses in the building and their coupling to the indoor air and solar radiation.

The report contains eight figures, two tables, and an appendix that presents a mathematical derivation of the interaction factors that account for interactions between components.

Conclusions: Frequency domain parameters determine the dynamic response of a building as a sum of component responses (in a manner analogous to steady-state heat-loss coefficient of a building being the sum of component heat-loss coefficients). These parameters can be determined graphically. Interactions among components can be accounted for naturally. It is expected that a simplified procedure can be developed based on a correlation between these parameters and overall building energy performance.

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Solar Report Summary

Issued January 1985

Annual Thermal Performance of Sunspace-Type Passive Solar Collectors for Residence Heating—Attached and Semi- Enclosed Geometries

R. D. McFarland

R. W. Jones

G. S. Lazarus

Los Alamos National Laboratory

Objective: To present results of annual-performance analysis for several sunspace passive solar heating systems.

Discussion: The sunspace is an important category of passive solar system for heating small- and moderate-sized buildings. (A sunspace can be thought of as being synonymous with a greenhouse without plants.) In this study, thermal network models were developed for several sunspace configurations. These configurations included two wall and thermal storage combinations. In one type, the common wall between the masonry, forms the major thermal storage component. In the other type, the common wall was a standard, lightweight, insulated wall, with thermal storage in the form of water drums in the sunspace. A number of physical geometries and glazing placements were simulated.

Annual simulations were made for 24 United States cities, using Typical Meteorological Year weather data. The simulations were made for 28 sunspace configurations and for five heating load coefficients, with and without R9 night insulation. The results of the simulations are presented in the form of the calculated annual solar savings fraction (SSF) for each configuration studied. The SSF is defined as the ratio of the decrease in required auxiliary heating to the total heating load.

Forty-two figures and ten tables complement the text. The details of the simulation and the results are presented in eight appendices.

Conclusions: Correlations were obtained between monthly SSF and monthly solar load ratio (SLR) to permit a simple estimate of auxiliary heat requirement in an building with an attached sunspace.

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Solar Report Summary

Issued June 1986

Influence of Prandtl Number on Natural Convection Heat Transfer Correlations

Mark S. Bohn
Ren Anderson

Objective: Present the results of research undertaken to determine the validity of measuring heat transfer coefficients that would be applicable to building interiors in small-scale, water-filled enclosures.

Discussion: Heat transfer in buildings, especially structures heated and cooled by passive solar techniques, is mainly controlled by natural convection. An interesting area is the sensitivity of natural convection, especially in enclosures, to the Prandtl number of the test fluid involved in the system.

This report presents previous work that focused on the effect of the Prandtl number on the Nusselt number and on the transition to turbulence. The experimental procedure is described. Modifications

to the cubical test cell allow testing in air for comparison with previous water data. The results of these experiments are included.

Two figures and three tables accompany the text, along with an explanation of nomenclature.

Conclusions: The Prandtl number does not have a strong influence on heat transfer in enclosures. Data from the air-filled enclosure indicate that heat transfer is reduced 10%-15% below the level that would be predicted from correlations based on water data. Although the effect of the Prandtl number on transition to turbulent flow is less well defined and requires some caution in interpretation, its effect seems small.

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Solar Report Summary

Issued June 1986

Heat-Transfer Enhancement in Natural Convection Enclosure Flow

Mark Bohn
Ren Anderson

Objective: Determine whether a roughened vertical surface comprising one wall of an enclosure exhibits greater natural convection heat transfer than does a smooth surface under conditions simulating the interior of a passively heated building.

Discussion: Natural convection from vertical direct-gain surfaces is a dominant method of heat transfer in passively heated buildings. This method of heat transfer is also very important in determining the performance of storage walls. A logical question is whether the surface heat transfer could not be increased by promoting transition of the boundary layer into turbulent flow.

The enhancement of natural convection heat transfer is studied in a water-filled test cell at Rayleigh numbers of $\theta(10^{10})$. Surface average heat transfer, local heat transfer, and flow visualization are compared for a vertical heated wall with either a smooth or a roughened surface. The height of the roughness,

distributed over the entire heated wall, is comparable to velocity boundary-layer thickness. The procedures and experimental errors involved in the testing of the roughened surface are included, as are visualizations of the natural convection flow.

Two tables and 13 figures are presented with the text. An appendix containing applicable boundary-layer equations is also included.

Conclusions: For an isothermal heated surface, the rough texture produced fully turbulent behavior at overall Rayleigh numbers that were about half the size as those for a smooth surface. This resulted in increases of about 40% in local heat transfer and about 16% in the surface average heat transfer. The constant-flux boundary condition did not exhibit early transition primarily because the experimental apparatus was not capable of achieving sufficiently high Rayleigh numbers.

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Solar Report Summary

Issued December 1986

Objective: Summarize the 26 projects completed under the U.S. Department of Energy's Marketable Products Program.

Discussion: The goal of the Passive and Hybrid Solar Program is to develop solar energy technologies that are economically competitive, technically viable, and an environmentally acceptable energy source for space heating, space cooling, hot water heating, and lighting systems. In an attempt to bring to the marketplace a variety of passive solar and hybrid materials and components that might be integrated into buildings, 26 projects were funded under the Marketable Products Program. The results of these projects are presented in this report.

Each project description provides information on the designer, the product, and the results obtained from the project. The results are divided into three categories, which indicate (1) whether or not the research generated data on a particular developmental aspect of a solar material, component, or system; (2) whether or not a project, though not developing a marketable product, contributed to state-of-the-art knowledge for

Results of the Department of Energy Passive and Hybrid Solar Marketable Products Program; Final Report

Mueller Associates, Inc.

that particular type of product; or (3) whether the product is being commercialized or is ready to be marketed.

Twenty-five tables and sixty-nine figures accompany the text. An executive summary is also included.

Conclusions: The report concludes that:

- Passive solar systems have progressed further for the residential sector than for the commercial sector.
- The simpler systems have been commercialized, leaving the more complex systems to either the federal government or the private sector for development funding.
- More complex or advanced systems (e.g., combined direct and indirect heat gain, hybrid systems, and multizone systems) require more research and development.
- Passive cooling systems still require extensive development to produce commercially available products.

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Solar Report Summary

Issued April 1989

Objective: Evaluate the impact of various roof aperture designs and orientations on the lighting, cooling, and heating requirements of small commercial buildings.

Discussion: The research group used data from previous research on roof apertures to provide input to BLAST 3.0, a thermal performance computer simulation tool. BLAST was used to analyze the performance of buildings in three climates with a variety of roof apertures. The results are presented for New York, Atlanta, and Los Angeles.

The prototype building is a 10,000 ft² single floor commercial space. BLAST was used to model the complex mechanical systems interactions that occur when each parameter is independently evaluated. The introduction of roof apertures changes the roof thermal conduction, available light for use in the space, reduction of the necessary artificial lighting needs and the corresponding heat produced by those lights, and the heating and cooling requirements of the space. The lighting and thermal effects were estimated for each type of roof aperture system. Roof apertures included horizontal glazing (skylights), angled glazing, and vertical glazing of various sizes and orientations. Detailed results are presented for the Atlanta climate in three basic aperture groups: (1) vertical glazing facing north, south and both

Impact of Glazing Orientation and Tilt on the Energy Performance of Roof Apertures

W. Place
P. Coutier
M. Fontoynt
R. Kammerud
B. Andersson
F. Bauman
W. L. Carroll
M. Wahlig
T. L. Webster

directions, (2) tilted glazing facing north, south and both east and west, and (3) various combinations of vertical glazing. The report includes 19 figures, the majority showing the annual operating cost of the various options.

Conclusions: The introduction of roof apertures dramatically reduces the artificial lighting needs of the prototype building in all climates. Along with the reduction of lighting, the cooling needs decrease and a slight increase in heating is apparent for low aperture sizes. The highest cost benefit ratio is achieved by the use of small (2% of floor area) horizontal apertures (skylights) yielding a savings of \$18/ft² of glazing per year. It is pointed out that this may not be the best overall option, however. The highest cost savings per unit of floor area is a roof aperture with vertical glazing that can face south or any combination of orientations including south (e.g., north and south). It is estimated that this system will save \$.04/ft² per year. With a glazing area equal to 8% of the floor area, the savings would be \$5/ft² of glazing per year. It should also be noted that the utility rates in a particular area have a substantial effect on the cost savings.

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Solar Report Summary

Issued April 1989

Objective: Evaluate the interaction between building parameters and the comfort and activities of the building occupants in two passive solar commercial buildings.

Discussion: The two buildings that were evaluated are part of the DOE Non-Residential Experimental Passive Buildings Program. Both the Mt. Airy Library and the Community United Methodist Church buildings have undergone extensive monitoring activities to evaluate various aspects of the heating, lighting, and ventilation systems. Four issues were evaluated in terms of their effects on energy use and comfort of the occupants: the amount of thermal mass and the area of mass exposed to possible solar gains, night set-back strategies, amount and location of acoustic treatment, and the shading of the solar collection areas. Both buildings were modeled using a computer simulation of building energy performance (BLAST). From these simulations, four periods of 10 days (one in each of the four seasons) were evaluated in detail.

Both of the buildings have large amounts of thermal mass, with large solar gain areas and little acoustic treatment. This evaluation used the computer simulation based on the two buildings to evaluate the possible changes that could have been made in the buildings to improve the thermal, visual, or auditory comfort of the occupants. Changes in mass include cutting the mass area in half and removing it completely. Setback options included removing the setback, cutting down the thermal mass, and reducing the glazing area. Acoustic treatments were evaluated

Effects of Occupant Issues on the Energy Performance of Two Existing Passive Commercial Buildings

B. Andersson
R. Kammerud
P. Albrand
M. Kantrowitz
M. Adegran
T. Webster

for the ceiling, wall, and floors. Shading analysis was done differently for each building. Mt. Airy was evaluated using the shades that are presently installed, in different configurations, and the CUMC building was evaluated using 70% reflective shades in the roof apertures.

The report includes 13 figures and an appendix that includes hourly graphs of the parametric runs.

Conclusions: Passive solar buildings, particularly those that have substantial amounts of thermal mass, must be evaluated carefully to provide the best balance between occupant comfort and the operational issues such as daylighting, heating, thermal lag, and cooling. Four basic conclusions were reached on the parameters that were evaluated. Thermal mass should be carefully designed to meet the functions of the building, operating schedule, etc. A mismatch between the two can result in poor energy performance and occupant discomfort. Typically, one should choose between an aggressive mass strategy or one with minimal mass. Winter night setback of a heating system in heavy mass buildings should be eliminated or severely restricted. Appropriate acoustic treatments can be used without dramatically affecting thermal performance of the buildings. If fixed shading is incorporated in the building to limit summertime solar gains, the occupants can have a great deal of flexibility in adjusting interior shades without seriously affecting the thermal performance. Adjustment of the shades in winter, however, can greatly effect the performance.

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Solar Report Summary

Issued April 1989

Objective: Evaluate the performance characteristics of a linear roof aperture daylighting system using a scale model outdoor test facility.

Discussion: An inch-to-the-foot architectural model was created with linear roof apertures to evaluate the performance of the daylighting system under various conditions and orientations. The model was mounted on a heliodon and light measurements were taken under actual clear sky conditions.

The results of the tests were recorded by an array of 35 photometric sensors located in two different configurations on the interior of the scale model. In addition to the illumination measurements on the interior of the model, there were measurements of the beam radiation and diffuse radiation components. A specially developed sensor was used to record the transmitted solar radiation to the interior surface. The sensor, an Integrating Window Pyranometer (IWP), uses a heat flux transducer with the back side ventilated to provide data on the amount of radiation available on the interior of the model.

Two basic configurations were evaluated with some intermediate changes being examined. The first configuration was an open floor plan. The second used a variety of office partitions. Special tests were run on nonreflective walls and roofs and the introduction of overhead light fixtures and air ducts. The daylighting system consisted of sloped, south-facing, double-pane roof glazing located at the top of a sawtooth clerestory design. To control glare and properly disperse the beam sunlight over the work plane, a good diffusing glazing was used for the inside pane of the

The Experimentally Measured Performance of a Linear Roof Aperture Daylighting System

F. Bauman
W. Place
B. Andersson
T. C. Howard
J. Thornton

roof aperture. The net aperture area was about 17% of the floor area. Eight building orientations were examined, relating to the seasonal changes for a latitude of 36 degrees north.

The report includes 15 figures showing the model and the experimental results.

Conclusions: Under clear sky conditions, the roof aperture system provided more than sufficient illumination on the work surface. There was relatively little change in the system performance over the year due to the highly diffuse inner glazing layer. This diffusing glazing provided a quite uniform illuminance distribution over the entire work plane as there was only a 15% reduction in the available illumination on the side walls compared with the centerline for all tested conditions. Lowering the reflectance of the roof and walls from white (84% reflectivity) to black (4% reflectivity) reduced the overall performance by up to 20% for the roof and 30% for changes in the walls. Interior partitions also result in a loss of performance. The 5-ft, 10-in partitions resulted in an 11% reduction and the taller 7-ft partitions had an 18% reduction. Overhead obstructing duct work had the most noticeable effect on the performance. White ducts (dowels representing three 18-in ducts) reduced the performance by 21%; painting them red reduced the performance by an additional 20%. Overall, the system resulted in fairly even light levels across the floor plan and throughout various seasons. Internal features and colors have an important relationship to the total performance of the lighting system.

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Solar Report Summary

Issued April 1989

Objective: Evaluate the visual performance factors and the occupant interaction with the lighting and control systems in a passive solar commercial building.

Discussion: The analysis of the visual environment was measured in a variety of spaces in the library. This information was coupled with observation of various visitors and library personnel. Data were compiled over a week in the summer and a week in the winter.

Each of the five spaces evaluated was reported in terms of three factors: (1) occupant interaction, (2) visual comfort, and (3) visibility. The occupant interaction was gathered through observation of the response to the environment and through interviews with both visitors and library staff. Items in this section included the use of artificial illumination, use of shades, and sitting in certain positions or places in the library. The visual comfort can be determined by a number of factors that are considered important for the overall comfort of the occupants, such as illuminance levels, light distribution, and contrast ratios. Visibility is the ease of performing the required visual tasks, requiring the measurement of relative illuminance and contrast.

Occupant interaction was gathered, in part, from a questionnaire (attached in the appendix) and

Mt. Airy Library: A Qualitative Study of Daylight in a Passive Solar Commercial Building: Investigation of Occupant Response and Visual Performance

M. Adegran
B. Andersson
W. Place

examining the physical environment. Such items as task lights that are being used, the use of overhead lights, and the adjustment of shading devices were recorded.

The visual comfort measurements were completed with a spot photometer. Measurements were made during the day, as well as profiles taken at night, to show the contribution from the artificial lighting system. Visibility was recorded by the use of a camera system that was set up to produce consistent photographic images of test material in each of the spaces that was evaluated.

The paper has 22 figures and eight appendices. The appendices include a glossary, samples of the occupant questionnaires, and other supporting material.

Results: In most areas the illuminance was below the traditional standards; however, the occupants enjoyed the levels that were provided. This might, in part, be based on the generally good contrast rendition. Daylighting meets most of the lighting needs of the building, even under the most overcast conditions (glazing area is 26% of floor area). The stacks and the children's area are exceptions to this and require additional illumination. Task lights are used frequently by the patrons but the overhead lights and shading devices are not. Glare was not a significant problem.

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Adegran, Mari; Anderson, Brandt; and Place, Wayne. (1986). "Daylighting in the Mt. Airy Public Library." *Passive Solar Journal*. Vol. 3 (No. 4); pp. 349-386. Work performed by Building Systems Analysis Group,

Lawrence Berkeley Laboratory, Berkeley, California. Reprints of the article are available from ASES (American Solar Energy Society), 2400 Central Ave., Suite B1, Boulder, CO. 80301.

Solar Report Summary

Issued April 1989

Effects of Daylighting Options on the Energy Performance of Two Existing Passive Commercial Buildings

B. Andersson
M. Adegran
T. Webster
W. Place
R. Kammerud
P. Albrand

Objective: Evaluate the effectiveness of the daylighting systems and the interrelationship between daylighting and the control systems used for backup electric lighting systems.

Discussion: The two buildings that were evaluated are part of the DOE Non-Residential Experimental Passive Buildings Program. Both the Mt. Airy Library and the Community United Methodist Church buildings have undergone extensive monitoring activities to evaluate various aspects of the heating, lighting, and ventilation systems.

This study was designed to evaluate the overall effects of a variety of lighting control strategies and the effect of those changes on the overall operation of the environmental control systems. Short-term monitoring was done in each of the buildings to determine the electric lighting use under a variety of sky conditions. A physical model was then used to create a "map" of the light distribution in the spaces. The maps were then created for a wide variety of sun angles and sky conditions. From this data the researchers were able to use yearly weather data to create a computer

model of the lighting conditions that would be experienced in the buildings during a typical year. A large computer simulation model (BLAST) was used to vary the lighting control strategies and provide information on the performance of the lighting, heating, and cooling systems in the buildings.

Eight figures and two tables are presented in the paper.

Conclusions: Computer simulations based on measured manual lighting control activity showed that manual control of the electric lights performed as well or better than simple automatic controls. This may be because of the large south apertures that were used in both locations. These systems allow for the lights to be off for extended periods of time. The occupants were also satisfied with lighting levels that were below commonly accepted standards.

Large south apertures contribute more to off-setting the electric lighting load than the heating load. With appropriate shading, large increases in the cooling load can also be avoided in climates with significant heating loads.

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Andersson, Brandt; Adegran, Mari; Webster, Tom; Place, Wayne; Kammerud, Ron; Albrand, Patrick. (1987). "Effects of Daylighting Options on the Energy Performance of Two Existing Passive Commercial Build-

ings." *Building and Environment*. Vol. 22 (No. 1); pp. 3-12. Available from Pergamon Press, N.Y.



Photoconversion/ Chemical

The term photoconversion refers to chemical or biological process by which solar energy is converted directly into other forms of energy, such as liquid and gaseous fuels, chemical feedstocks, electricity, and latent heat. Photoconversion differs from biomass conversion because it is a direct, single-step, light-driven process that starts with simple substances such as water, carbon dioxide, nitrogen, and simple organic compounds.

When sunlight strikes photoactive molecules or solids it can excite their electrons and initiate chemical reactions. A well-known example of photoconversion is photosynthesis, whereby green plants convert sunlight to stored chemical energy in the form of carbohydrates. Some researchers are trying to manipulate the physiology of simple plants (algae) and bacteria by modifying their composition, structure, or environment so that they produce hydrogen, fixed nitrogen, hydrocarbon fuels, or electricity rather than carbohydrates. This photoconversion process occurring within living organisms is called *photobiological conversion*.

Other types of photoconversion include *photochemical conversion* and *photoelectrochemical conversion*. Photochemical conversion involves molecules that can absorb sunlight and subsequently drive reactions that produce fuels and chemicals. In photoelectrochemical conversion the photoactive components are solid semiconductor materials that produce fuels and chemicals on their surface when illuminated or in contact with certain liquids.

The conversion efficiency of solar energy by growing plants is only 0.1 percent to 2 percent. The theoretical conversion efficiencies of photobiological and photochemical systems are much higher—20 percent to 35 percent. Such high efficiencies make photoconversion an attractive and economically viable solar energy option.

Much basic research is being done to realize the great potential of photoconversion processes for the production of fuels and chemicals from sunlight.

SERI Report Summary

Photobiological Production of Hydrogen- A Solar Energy Conversion Option

Paul Weaver
Stephen Lien
Michael Seibert

Objective: Review the field of photobiological hydrogen production and assess its potential for applied conversion systems.

Discussion: The two general classes of enzymes, hydrogenase and nitrogenase, that catalyze hydrogen metabolism are discussed. The technical feasibility of employing biological systems to produce hydrogen at the direct expense of light energy are examined. Both the whole-cell and cell-free systems are considered. Problems to be surmounted before photobiological solar energy conversion is technically feasible are detailed. Possible approaches to some of the problems are also presented.

The text is supplemented with five detailed figures and five tables.

Conclusions: None of the currently identified photobiological hydrogen-producing systems have reached the development point at which pilot plant operations would be of benefit. Current prospects for near- to mid-term applications rest mainly with the whole cell systems, including those using cyanobacteria or photosynthetic bacteria. Research should continue emphasizing:

- surveys of naturally occurring strains including marine and thermophilic organisms to identify those having the most active hydrogen metabolism,
- selection of mutant organisms with constitutive derepression of hydrogenase and nitrogenase (which would result in higher evolution rates and a good source of enzyme for cell-free systems,
- genetic manipulation of cellular metabolism to maximize hydrogen photoproduction; and
- studies identifying the environmental conditions leading to optimal hydrogen production.

Long-range applications should emphasize cell-free systems based on the hydrogen photoproduction pathway found in green algae. Specific research directions in this area should emphasize:

- detailed studies of the active site(s) of hydrogenase and nitrogenase which would aid in the synthesis of stable, active analogues for use in applied systems;
- stabilization of hydrogenase;

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- stabilization of the photosynthetic membrane, in particular with an oxygen evolution associated with the second of two sequentially linked photochemical reactions (PSII); and
- biochemical and biophysical studies of water splitting and reaction center mechanisms that may give insight into the development of chemical analogues.

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Solar Report Summary

Issued June 1986

Photoelectrolysis of Water for Production of Hydrogen

Final Subcontract Report
1 March 1979 — 8 March 1981

Lincoln Laboratory

Objective: Investigate three different approaches to fabrication of catalytic electrodes for photoelectrolysis of water.

Discussion: The approaches studied included the use of composite structures, solid solutions, and modified surfaces. Composite structures were prepared by depositing sputtered CdSe-SrTiO₃ (cadmium selenide-strontium titanate) and CdSe-TiO₂ (cadmium selenide-titanium oxide) films on CdSe substrates. Solid solutions of TiO₂ with oxides of tantalum, tungsten, vanadium, and molybdenum, and of SrTiO₃ with lanthanum iron oxide, strontium vanadium oxide and strontium molybdenum oxide, were prepared

primarily by ceramic techniques. CdSe and SrTiO₃ surfaces were modified by argon ion bombardment. These three approaches were evaluated by characterizing and testing electrodes fabricated from materials prepared by each method. The tests included measurement of current-voltage characteristics, spectral response, and chemical stability during operation in electrochemical cells.

Thirty-one figures are included. Two related journal articles are presented as appendices.

Conclusions: None of the three approaches investigated produced efficient photoelectrolysis electrodes.

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Photovoltaics

Other solar technologies that produce electricity do so by employing some form of solar energy to drive a motor. Photovoltaics (PV) is unique in that it uses solar energy directly. Semiconductor devices called solar cells generate electricity whenever sunlight hits them.

Solar cells have been used for 20 years to power satellites and manned vehicles in space. They now promise to help tap the sun's energy on earth, producing electric power in an increasing number of cost-effective applications.

Most solar cells today are made from silicon. Each cell is composed of two very thin layers. Small amounts of different materials are added to the silicon of each layer, giving one layer a negative electrical bias (n-bias, an excess of electrons) and the other layer a positive bias (p-bias, a deficiency of electrons). Terminals of an external electrical circuit are attached to the front and back of the cell. When sunlight (specifically, photons of energy) penetrates the surface of the cell it knocks electrons loose from some of the silicon atoms, leaving "holes" in the atomic structure. Because of the electrical bias built into the cell the free electrons move into the negative layer, create a voltage, and allow an electric current to be drawn through an external circuit. If a load, such as a direct current

(d. c.) electric motor is placed in the circuit, it will be operated by the current.

Cells can be connected in either parallel or series and are enclosed in a sealed glass or plastic unit called a module. Any number of these modules are then positioned into a rigid frame to provide a specific power rating. These framed units, called arrays, can then be set up in array fields of any size. Another approach is to use concentrating collectors to focus sunlight on solar cells and tracking equipment to keep the concentrators aimed at the sun throughout the day. The wide applicability of PV technology is enhanced by this modularity. A photovoltaic system sometimes includes a storage medium (usually batteries) to provide power at night or during cloudy weather. Power conditioning equipment is also needed if the load requires alternating current (a.c.), since solar cells produce d.c. electricity. Power conditioning also allows PV systems to be integrated with other electrical generating equipment and the utility grid.

Research focuses on developing manufacturing technology to help reduce costs of the traditional single-crystal silicon cell and on producing solar cells from less expensive materials. Promising alternatives include thin films of amorphous silicon, copper sulfide/cadmium sulfide and gallium arsenide.

SERI Report Summary

Photovoltaics Research Annual Report- FY78 (Task 3210) for Period 10/1/77-9/30/78

Larry L. Kazmerski

Objective: Contribute to the development and demonstration of intermediate efficiency (greater than 10 percent) amorphous or polycrystalline thin-film cells, and high efficiency (greater than 30 percent) photovoltaic devices.

Discussion: The SERI photovoltaics research program was initiated as part of the FY78 Annual Operating Plan. During FY78, the photovoltaics program provided the basis for future branch research by initiating research efforts which were identified and defined in other branch tasks; coordinating research activities with the design and development of the SERI in-house (interim) laboratory; and identifying feasible, cooperative research efforts with other laboratories.

Nine program areas were identified both as integral parts in the FY78 photovoltaics research plan and as a basis for building FY79 and subsequent research programs:

1. solid-state and device theory
2. very high efficiency cells (III-V, single crystal semiconductor devices)
3. intermediate efficiency thin film cells (amorphous silicon devices)

4. silicon purification
5. silicon crystallization
6. device processing
7. advanced technologies (spray and paste techniques)
8. surface and interface analysis
9. measurement development

Descriptions and the status of research areas which were initiated under the photovoltaics research task during FY78 are summarized in the report. An anthology of scientific publications and presentations which resulted as a part of the task are also included.

Conclusions: Accomplishments during FY78 included:

- growth of the first ternary semiconductor by molecular beam epitaxy (MBE) and the fabrication of the first MBE copper indium selenide/cadmium sulfide heterodiode for photovoltaic investigations;

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- development of an accurate solar spectrum (SOLTRAN) for photovoltaic applications and dissemination to Department of Energy Advanced Research and Development contractors;
- modeling of polycrystalline heterojunction solar cells, emphasizing grain boundary and interface mechanisms;
- prediction of heterojunction and multijunction solar cell performance based upon SOLTRAN;
- characterization of semiconductor thin films on conductive substrates;
- Auger Electron Spectroscopy/Secondary Ion Mass Spectroscopy (AES/SIMS) evaluation of impurity segregation in multicrystalline silicon;
- AES/SIMS investigation of interdiffusion, especially grain boundary diffusion, in copper-ternary, thin-film solar cells; and
- acoustic microscopy studies of multigrained silicon.

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SERI Report Summary

Photovoltaic Venture Analysis, Final Report, Volume I: Executive Summary

Dennis Costello
David Posner
Dennis Schiffel
James Doane
Charles Bishop

Objective: Present the results of the Photovoltaic Venture Analysis.

Discussion: The Photovoltaic Venture Analysis is a study of an eight-year, \$380 million program spanning fiscal years 1979-1986 in which the federal government subsidizes the difference between the price charged by photovoltaic producers and the maximum price the consumer will pay. The program is called the "procurement initiative" or the "market pull initiative."

The primary objectives of the venture analysis are to estimate the benefits and costs of the market pull initiative and compare the market pull initiative to other possible government approaches to accelerating the commercialization of photovoltaics.

The report describes potential markets for photovoltaic systems, and the response of the photovoltaic supply industry to those markets is then considered. Using a model which calculates the economic benefits of various government subsidy programs and integrates the supply and demand characteristics of photovoltaics over time, results are presented for different supply, demand, and economic conditions.

The report is presented in three volumes. The body of the report and the Executive Summary are in

Volume I. Volumes II and III present details of the analytical assumptions, results of the analysis, and background information. Twenty figures and 50 tables complement the text.

Conclusions:

- The market pull initiative is not an effective mechanism to achieve the required photovoltaic price reductions.
- The impact of the initiative on grid competitive markets is probably small.
- The value of the market pull initiative depends on the goals of the Department of Energy.
- The benefits of a price reduction breakthrough outweigh the benefits of the market pull initiative.
- The market pull initiative should not be implemented until market conditions necessary for its success arise.
- Research and development on photovoltaic technologies should be increased.
- Effective policies for accelerating the commercialization of photovoltaics should be identified.

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SERI Report Summary

Objectives and Strategies of the International Photovoltaic Program Plan

Solar Energy Research Institute

Dennis Costello
David Posner
Robert Koontz
Patricia Heiferling

Jet Propulsion Laboratory

Paul Carpenter
Lewis Perelman

Objective: Describe the International Photovoltaic Program (IPP) plan and delineate its objectives and strategies.

Discussion: The report begins with a background discussion of photovoltaics, photovoltaic system technology, and the market for photovoltaic systems. Then, the research plan for IPP is presented, with emphasis on the development of an international plan to demonstrate and promote the use of photovoltaics in other nations. Finally, the strategies and tactics of IPP are presented. The International Solar Commercialization Working Group's role in this plan is discussed.

Conclusions: The primary objective of IPP is to accelerate the widespread use of photovoltaic systems in international markets. In achieving this objective, the program will produce a number of significant benefits, in that it will:

- maintain, stabilize, and foster expansion of the U.S. photovoltaic industry by promoting world-wide exports;
- contribute to the economic, political, and social advancement of developing countries;

- improve the U.S. balance-of-trade position;
- reduce the growth rate of worldwide demand for oil which will lead to easing of competition for limited supplies for oil, reduction of upward pressure on oil prices, reduction of balance-of-payments deficits of many countries, and lessening of oil-associated environmental impacts.

The following quantitative goals have been set for the domestic photovoltaic industry:

- double the production of photovoltaic energy systems each year during the decade starting with FY79;
- reduce the average cost of installed solar photovoltaic energy systems to \$1 per peak watt by FY88; and
- stimulate private buyer purchases of at least 90 percent of all solar photovoltaic power systems produced in the United States during FY88.

It is the goal of the IPP to promote the expansion of photovoltaic production so that 60 percent to 75 percent of the U.S. photovoltaic systems produced

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are sold in foreign markets between FY79 and FY85.

The following components will be critical elements in the IPP strategy:

- photovoltaic system demonstrations;
- information gathering for suppliers;
- information dissemination for marketing;
- administrative actions to expedite marketing;
- financial incentives; and
- monitoring, assessment, and coordination between participating organizations.

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SERI Report Summary

Photovoltaic Procurement Strategies: An Assessment of Supply Issues

Dennis Costello
David Posner

Objective: Explore five possible photovoltaic procurement strategies through personal interviews with potential participants from various industries.

Discussion: To place photovoltaic procurement strategies in their proper perspective, an historical overview of federal procurement is in order. The federal government has faced the problem of organizing government purchases since the Revolutionary War. In Alexander Hamilton's time such functions were centralized in the Department of Treasury. With the nation's growth, individual agencies used their own initiative and budgets to obtain needed supplies.

In 1905 and through World War I, a General Supply Committee formed by Congress coordinated and controlled purchases, most of which were requirements for defense. After the war, cost-type contracts and contracts based on cost plus a percentage were common.

The Depression gave procurement a social conscience. Minimum wages were required under all federal contracts and efforts were made to upgrade working conditions, employ the handicapped, and in general promote other objectives that legislative

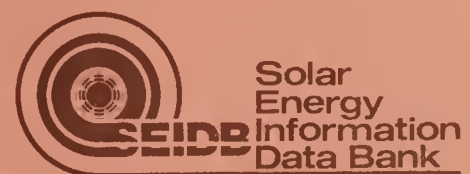
and executive orders were unable to accomplish. Negotiated contracts were the common mechanism for fulfilling defense needs during World War II.

In 1949, the General Services Administration was established and given authority over procurement policies of all federal agencies except the Department of Defense. Procurements were used to conduct the entire space program. It led to funds for research, development, and demonstration of technologies related to many civilian applications. Between 1953 and 1978, funding increased from less than \$1 billion to almost \$14 billion.

In 1974, an Office of Federal Procurement Policy was established within the Office of Management and Budget. Various kinds of contracts followed, some of them implemented in support of the development of semiconductors, destined to have a large defense as well as overall market. Experience here provided background for the survey used to determine the best procurement strategy for photovoltaics.

To focus the personal interviews, five sample federal procurement programs were outlined to 32 representatives of 13 major companies which were either current or potential producers of photovoltaics.

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Participants were informed of the nature of the various strategies. Included in the presentations were the magnitude of purchases required; and the type, duration, requirements, and number of contracts each strategy would involve. The value of each of the five strategies to the successful bidding company was estimated.

By broad definition, the strategies studied were as follows:

- (1) no-fixed price, with moderate budget;
- (2) fixed price, with moderate budget;
- (3) fixed price with an aggressive budget;
- (4) experimental production facilities and fixed-price buys; and
- (5) innovative product procurement.

Results were tabulated with each strategy's perceived advantages and disadvantages listed. One of the most interesting and important findings was that whereas all companies would be likely to bid on the no-fixed price, moderate budget strategy (No. 1), only a few companies would consider bidding the fixed price, moderate budget strategy (No. 2). Probably no company would bid on the fixed price, aggressive budget strategy (No. 3). Four companies, three of them electronics producers and one energy company subsidiary, would consider bids on experimental production facilities and fixed-price buys (No. 4) if no requirements for disclosure of technical information were made. Only one would bid if disclosure were required. Strategy No. 5, innovative product procurement, had a mixed reaction. Several current producers and potential producers with new production techniques would bid.

Participants perceived that strategies No. 1 and No. 5 would encourage industry competition, that No. 2 and No. 4 could lead to lower module prices. Few participants in the survey were willing to accept contracts lasting as long as five years, most feeling

that the technology was evolving too rapidly for extended-term commitments to prices and deliveries. Concern was also expressed for the escalating cost of polysilicon, essential to photovoltaic production. Response time for proposal submission would be generally shorter for large firms, better equipped and staffed to get their bids together.

An appendix to this report presents a profile of the photovoltaic industry today with trends in module sales and prices, and the characteristics and research and development activities of producing companies.

Conclusions:

- Significant differences exist between early government semiconductor procurements and photovoltaic procurements currently being considered.
- Small, cost-based procurements encourage industry diversity and provide performance information.
- Fixed-price contracts could stimulate short-term cost reductions but may change industry structure.
- Production facility subsidies and innovative product procurements are attractive to some companies.
- Procurement strategies should be matched with objectives.
- Effects of photovoltaic procurements on potential purchasers need to be examined.
- A clear statement of anticipated federal photovoltaic program procurements would magnify impacts, whereas programs that change frequently reduce the credibility of future programs, add to market uncertainty, and have a detrimental effect on industry planning.

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SERI Report Summary

International Photovoltaic Program Plan, Volume I

Solar Energy Research Institute

Dennis Costello

Robert Koontz

David Posner

Patricia Heiferling

Jet Propulsion Laboratory

Paul Carpenter

Sylvia Foreman

Lewis Perelman

Objective: Describe the tactics, budget, and benefits of the International Photovoltaic Program Plan.

Discussion: The International Photovoltaic Program Plan calls for the expenditure of approximately \$135 million in government funds, of which \$126.5 million would be from the Department of Energy (DOE), to accelerate the widespread use of photovoltaic systems in international markets.

After describing the objectives and background behind the plan, the report gives an overview of the program, with discussion of overall program strategy, program elements and tactics, timing and milestones, resource requirements, and relationship to domestic photovoltaic programs.

Following the overview, the five principal program elements and associated tactics are discussed in detail. The program elements discussed are:

- market demonstrations to show commercial buyers, government and private assistance organizations, and international financial institutions that photovoltaic systems are a viable and

competitive source for their energy system needs;

- systems development for use in specific international applications;
- supplier assistance designed to directly assist U.S. companies and affiliates to market photovoltaic systems;
- purchaser assistance to provide information about the performance, economics, and applicability of photovoltaic systems to potential users; and
- information clearinghouse to collect and disseminate information from the other four program elements.

The program management structure and the proposed budget for each of the five program elements is presented in detail. The final section of the report discusses the expected impacts and benefits of the plan. Volume 2 provides the appendices.

Thirteen figures and 22 tables complement the text.

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Conclusions: The program will:

- help to maintain, stabilize, and promote the photovoltaic industry by facilitating worldwide sales;
- contribute to the economic, political, and social advancement of the developing nations that utilize photovoltaic technology;
- reduce the rate of growth in worldwide demand for oil;
- help to improve the U.S. balance of trade; and
- encourage international scientific and technological cooperation.

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Standards for Photovoltaic Energy Conversion Systems Final Report

Harry A. Schafft

Objective: Search for existing domestic standards and related documents for possible use in the development of a system of standards for photovoltaic (PV) energy conversion systems.

Discussion: A search of the existing literature revealed approximately 150 documents related to

PV test methods, recommended practices, standards, and performance criteria. The documents are listed in Appendix A.

Conclusions: Few standards are directly applicable to terrestrial PV systems. Much standards development is needed to support PV commercialization.

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Solar Report Summary

Issued June 1986

Amorphous Thin Films for Solar-Cell Applications Quarterly Report No. 1 for the Period 11 September 1979 to 10 December 1979

D. E. Carlson
R. S. Crandall
J. Dresner
B. Goldstein
J. J. Hanak
A. R. Moore
J. I. Pankove
H. A. Weakliem

Objective: Report on work performed by the Display and Energy Systems Research Laboratory of RCA Laboratories, Princeton, N.J. for the period September 11, 1979, to December 10, 1979, under SERI Contract Number XJ-9-8254.

Discussion: The progress of amorphous thin-film research is given for the following topics:

- a new method for determining the drift mobility of majority carriers in doped a-Si:H,
- deposition and doping studies using a radio frequency magnetron discharge system,
- mass spectrometric studies of impurities in the SiH₄ discharge,
- a study showing the boron implantation of an i-n structure produces a p-i-n cell with an enhanced V_{oc} but reduced J_{sc} ,

- laser annealing at power densities up to 60 megawatts per square centimeter,
- the photo-Hall effect in undoped a-Si:H,
- the use of the photoelectromagnetic spectrum for the short-circuit to estimate hole diffusion lengths,
- fabrication of p-i-n cells with conversion efficiencies on the order of 4.5 percent,
- fabrication of solar cells with a-(Si,Ge):H alloys, and
- a study of the spectral dependence of the majority-carrier gain in a-Si:H solar cells.

Conclusions: Much significant progress was made during the period reported.

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Characterization and Assessment of Potential European and Japanese Competition in Photovoltaics. Final Report

Science Applications, Inc.

Objective: Assess the potential of European and Japanese firms to produce and market photovoltaic (PV) power systems internationally in competition with firms in the United States.

Discussion: The study consists of three distinct parts: (1) an overview of worldwide export activity which describes the general posture of selected European countries and Japan; (2) an assessment of European competition focusing on Germany, France, and the United Kingdom; and (3) an assessment of Japanese competition. This last section on the Japanese competitive position was based on a previous study by Science Applications, Inc. prepared for the Department of Energy, (*Export Potential for Photovoltaic Systems*, Preliminary Report, April 1979).

This study is limited in scope to an evaluation of existing literature in PV technology and international marketing trends. Data on specific Japanese and European marketing plans were not available for analysis during the study period. Within this framework, trends in worldwide competition are discussed, drawing as much on historical perspectives in allied fields as on market projections of PV systems. All research was conducted within the United States. Sources of data included published reports in the scientific, trade, and business press; firm's annual reports;

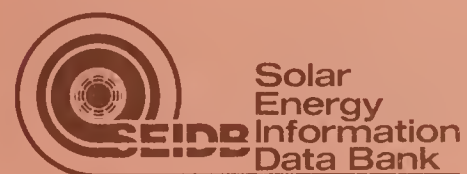
telephone interviews with representatives of European and Japanese firms; and a review of the findings of three U.S. groups that had recently toured Japanese photovoltaic firms. European and Japanese government representatives were also interviewed and government program descriptions evaluated.

Twenty-four figures complement the text.

Conclusions: The most important findings of the study are summarized as follows:

- Europe trails behind the U.S. in both technology development and PV product sales. U.S. manufacturers dominate the world market today. The U.S. is also in a lead position in most areas of European research and development (R&D) activity. The notable exception is the cast ingot polycrystalline effort in Germany.
- European firms are more active in the development of total systems for developing country markets. U.S. manufacturers supply the bulk of the PV cells and modules but European firms are instrumental in developing the markets.
- Europeans view PV systems primarily for developing country markets. French development funding over the last few years

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is responsible for the current Francophone Africa market activity. Results of this development funding include: broad French corporate interest in PV systems, the rising importance of the African market to PV manufacturers, and increasing joint ventures between U.S. PV manufacturers and French firms to tap this market.

- Europeans are capable of rapidly developing U.S. cell technology "break throughs" but only in select countries where applicable R&D activity exists. In contrast, the U.S. program is broad enough to follow European "break throughs" across the spectrum of PV R&D activities.
- The PV industry is largely comprised of multinational corporations which do not readily fit into the mold of being supportive of national export initiatives. Joint ventures with foreign firms, manufacturing overseas,

and shared R&D results are realistic business strategies which will become increasingly common as the foreign market develops.

- At present, Japan is not a major factor in the PV power system market; the U.S. is. Despite this fact, the authors believe that Japanese firms have the potential to capture the major share of the world market. This will become true if several assumptions are valid concerning the probability of technical and manufacturing breakthroughs in photovoltaic power: growth of market demand, a determined national push by Japan, and a lack of concerted effort to promote U.S. PV exporters. The most likely outcome that can be projected today is that Japan has the potential to capture a significant share of the international PV power market in about twenty years.

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SERI Report Summary

Issued June 1981

Fabrication and Characterization of ITO/Silicon SIS Solar Cells

Joel DuBow
Rajeshwar Krishnan
Rajendra Singh
Carl Wilmsen

Objective: Describe research to optimize the performance of indium tin oxide (ITO)/polycrystalline silicon solar cells.

Discussion: The objective of this project required the participants to identify performance limitations, identify major stability problems which might inhibit application of these devices, evaluate the impact of indium supply and price on applications, and evaluate the economic viability of ITO sputter-deposited solar cells. This report summarizes research to these ends, and assumes significant reader familiarity with the subject.

During the project, three device measurement techniques were introduced which assisted in improving cell efficiency. These were automated admittance and surface state analyses, noise spectral density analysis, and automated I-V and C-V analyses. These measurements were combined with other techniques to identify grain boundaries, intragrain defects, edge leakage, and interface losses.

Sixty-six figures and ten tables accompany the text. Three appendices list the educational credentials of the investigators, publications resulting from this work, and the research participants.

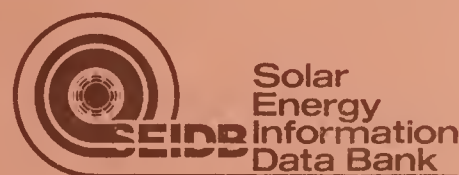
Conclusions:

- Several process modifications resulted in large area solar cells with high efficiency.
- The new measurement techniques led to alleviation of detected flaws through process modification.
- Further study is required to establish long-term device stability.
- Indium availability and price will not limit the use of ITO solar cells.
- Prototype cells should be produced using ITO sputter deposition.

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Issued June 1981

Cadmium Sulfide/Copper Sulfide Heterojunction Cell Research Final Report, February 26, 1979-July 15, 1980

John A. Thornton
David G. Cornog

Objective: Report on cadmium sulfide/copper sulfide heterojunction research work performed by the Telic Corporation during the period February 26, 1979, through July 15, 1980.

Discussion: During the report period, work performed included extensive modifications to deposition apparatus at Telic, investigation of cadmium sulfide (CdS) resistivity control by indium doping and off-stoichiometric deposition, study of the copper sulfide (Cu₂S) deposition process, and

sputter deposition of Cd(Zn)S/Cu₂S photovoltaic cells.

Conclusions: Cadmium sulfide resistivities in the range 0.1 to 5 ohmcentimeter were obtained for target doping levels of 0.1 to 1 atomic percent of In. These resistivities were found to be sensitive to the hydrogen sulfide injection rate. Copper sulfide coatings deposited on cadmium sulfide were found to have the same properties as those deposited on glass substrates in previous work. Sputter deposition of Cd(Zn)S/Cu₂S cells yielded efficiencies from 0.4 percent to 1.2 percent.

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Issued November 1982

Atmospheric Effects on Solar Cell Calibration and Evaluation

R. E. Bird

R. L. Hulstrom

Objective: Illustrate atmospheric effects on photovoltaic cell short-circuit currents and cell calibration numbers for silicon, gallium arsenide, and cadmium sulfide.

Discussion: Rigorous radiative transfer computer codes are used to illustrate the effects of precipitable water, turbidity, air mass and global normal irradiance (compared with direct normal irradiance) on solar cell performance.

Thirteen figures and three tables are included in the report.

Conclusions:

- Rigorous radiative transfer codes are essential for calculating the scattered irradiance component.
- Precipitable water vapor in amounts between one and four centimeters caused solar cell number to vary for direct normal radiation by 1.7 to 4.6 percent. All of the cells modeled showed less than a two percent variation except for gallium arsenide, which showed a 4.6 percent change in calibration number.
- Increases in air mass from 1 to 2 changed cell calibration number for direct normal radiation by 1.0 to 2.6 percent.
- Increasing turbidity from 0.1 to 0.27 at 500 nanometers wavelength for direct normal radiation

changes the calibration number by 1.4 to 3.1 percent.

- Changing water vapor, air mass, and turbidity simultaneously by the total amounts specified above varies the cell calibration number for direct normal radiation by 4.5 to 8.0 percent.
- The atmospheric effects on the cell calibration number are much more difficult to predict than those on cell short-circuit current.
- Water vapor has little effect on cell short-circuit current for direct normal radiation when compared with the effects of air mass and turbidity.
- Turbidity changes have little effect on the short-circuit current for global radiation when compared with direct normal radiation.
- The global normal-to-direct normal irradiance ratio should be less than approximately 1.3 to conform to the reference cell calibration specification of the draft ASTM standard that the product of the Angstrom-turbidity coefficient with the air mass be less than 0.25.
- For certain atmospheric conditions, global calibration methods for reference cells have a greater dependence on air mass than normal calibration methods do.
- The gallium arsenide cell analyzed is significantly more efficient for applications in high water-vapor conditions than in dry conditions.
- The CdS/Cu₂S cell analyzed is much more efficient for flat-plate applications than for concentrator applications under most atmospheric conditions.

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Environmental, Health, Safety, and Regulatory Review of Selected Photovoltaic Options (Copper Sulfide/ Cadmium Sulfide and Polycrystalline Silicon)

Kathryn Lawrence

Sue Morgan

David Schaller

Thomas Wilczak

Objective: Review the environmental, health, safety, and regulatory impacts of selected copper sulfide/cadmium sulfide and polycrystalline silicon photovoltaic cells.

Discussion: Polycrystalline silicon (poly-Si) and copper sulfide/cadmium sulfide ($\text{Cu}_2\text{S}/\text{CdS}$) photovoltaic systems are two of several developing technologies that could emerge as commercial products. This report presents an overview of the life-cycle environmental, health, and safety effects that could result from a photovoltaics industry based on poly-Si or $\text{Cu}_2\text{S}/\text{CdS}$ solar cells and examines the regulatory programs applicable to their manufacture, use, and disposal. Environmental, health, and safety risks are discussed in Part I. Part II examines major regulatory programs that may apply to the poly-Si and $\text{Cu}_2\text{S}/\text{CdS}$ technologies.

Twelve figures and 57 tables are included. Four appendices cover details of waste stream treatment, list associated industries, summarize relevant standards, and give details on selected pollutants regulated by the Environmental Protection Agency.

Conclusions: Water quality, solid waste disposal, and occupational health and safety regulations are likely to rate highest consideration for commercial-scale photovoltaic production. However, currently available control technology appears to be sufficient to treat solar cell fabrication wastes. Final determination of photovoltaic industry compliance with government regulatory programs will require quantitative data from demonstration and commercial-scale facilities.

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The Growth of Silicon Sheets for Photovoltaic Applications

Thomas Surek

Objective: Review and compare four "fast" ribbon growth processes for silicon sheets — dendritic-web growth (WEB), edge-defined film-fed growth (EFG), ribbon-to-ribbon growth (RTR), and the silicon-on-ceramic process (SOC) — and identify some of the problems that need to be resolved.

Discussion: Silicon sheet growth processes are classified by their linear growth rates. Then the "fast" growth processes are ranked by criteria involving growth stability, sheet productivity, impurity effects,

crystallinity, and solar cell properties. The status of more rapid silicon ribbon growth techniques, such as horizontal ribbon growth and ribbon quenching, is also reviewed. The emphasis of the discussion is on examining the viability of the produced sheet materials as solar cell substrates for low-cost silicon photovoltaic systems.

Conclusions: Low-cost silicon photovoltaic systems will probably be achieved. However, at this time it is not possible to choose among the various sheet growth processes.

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Photovoltaic Systems Development: Best Loca- tions for Near-Term Residential Applications

Gregg Ferris
Gennifer Sussman
Tom Thomas

Objective: Identify urban locations where residential photovoltaic (PV) systems can reasonably be expected to be developed in the near future, and rank 25 best locations for PV development according to Standard Metropolitan Statistical Areas (SMSAs) in the continental United States.

Discussion: Photovoltaic costs and values used in this analysis are based on U.S. Department of Energy (DOE) estimates and forecasts. The analysis assumes, first, that all state and federal policies affecting the price of PV systems in 1980-1981 will be in effect in 1984. Thus, DOE cost goals for PV systems are reduced to reflect various state and federal subsidies applicable in 1980-1981.

The method used to identify likely urban areas is conjoint analysis. First, each SMSA's potential as a market for residential PV systems is determined. Second, a small set of location descriptions is derived from the SMSA data which represent the variations in the full set of SMSA descriptions. Third, the represen-

tative location descriptions are ranked according to expert decision makers' evaluations of each location's market potential. Fourth, the rankings assigned by the experts are evaluated by means of regression equations to derive weights for defining the relative importance of each set of location characteristics. Finally, the weights derived in this process are applied to actual collected data and the SMSAs are ranked accordingly.

The 95-page report contains seven figures and twelve tables in the text, and several tables in the three appendices.

Conclusions: The results of the analysis indicate that several areas seem to hold considerable potential for residential PV development — particularly clusters around New York, Los Angeles, and San Francisco. Current research into systems integration should enable us to better understand the electric load profile of a residential unit and how to match PV output to the load.

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Plan for a Photovoltaic Applied Research Laboratory for Developing Countries

S. Hogan
K. Firor
T. Ciszek
J. Olson
S. Wagner

Objective: Present a four-year manpower and financial plan for an applied research photovoltaic laboratory in a developing country.

Discussion: A photovoltaic applied research laboratory such as discussed in this report would provide the necessary educational experience to implement fully photovoltaic manufacturing, as well as provide a modest production capability.

Two scenarios are presented to detail different financial investments. The first requires \$500,000 to develop the laboratory so that module production will reach 1000 watts by the fourth year. The second scenario is an expanded version of the first, calling for a produc-

tion capability of 10 kilowatts by the fourth year, and entailing an additional cost of \$326,000. All costs presented are restricted to materials and equipment; personnel and overhead costs are not included.

Information is also given about the purification of silicon and the growth of single-crystal boules as an optional addition to the plan. Initial costs for set-up of the facility vary depending on whether a research or production approach is taken.

Conclusions: Establishment of an applied research photovoltaics laboratory in a developing country is feasible, if funds are available to do so. Such a laboratory would provide both educational and production experience to the establishing country.

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Advanced Photovoltaic Trough Development

R. Spencer
K. Yasuda
B. Merson

Objective: Present results of the advanced photovoltaic trough concentrator project performed by the Acurex Corporation under Department of Energy funding through Sandia National Laboratories.

Discussion: The goal of the reported work was to develop a single axis photovoltaic trough concentrator which combined high efficiency, effective cell encapsulation, and improved array life. The project included three primary tasks. The first task, Array Optimization, was an analytic study to optimize the array configuration. The second task, Advanced Reflector Development, included development of thin glass mirror laminates as reflective surfaces, performance characterization of glass reflectors, and modification of existing photovoltaic trough designs. The final task, Advanced Receiver Development, was to design and

test advanced receivers with high efficiency and effective encapsulation. These tasks were performed interactively, with the results of analysis, design, and testing within each task being fed back into the other tasks to fulfill the project objectives most effectively.

An executive summary is included as the first section of the report. There are five appendices, 82 figures, and eleven tables.

Conclusions: As a result of this work, the designs of the receiver and its reflective surfaces were improved. In-depth understanding of the performance of the single axis photovoltaic trough was obtained for varied operating conditions. An empirical model that was developed includes all pertinent variables and will adequately predict trough performance.

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The Design of a Photovoltaic System for a Southeast All-Electric Residence

E. M. Mehalick
G. F. Tully
J. Johnson
N. Truncellito
R. Schaeffer
J. Parker

Objective: Develop a photovoltaic (PV) system for a single-story residence suitable for the southeast region of the United States.

Discussion: The PV system design described in this report is for a residential single-story house located in the southeast region of the country typified by the Miami/Charleston environment. The house is assumed newly constructed in 1986 with a living floor area of 161 square meters and a rectangular south facing roof area of 86 square meters. The design includes energy conservation and passive solar features projected for 1986. An advanced performance three-ton heat pump is used for heating and cooling and there is an electric hot water heater. Options for supplementing hot-water heating with solar thermal collectors and for waste-heat recovery units can be included in the design without changing the PV system design.

The electric energy derived from the PV system serves the normal household electrical requirements including general appliances, lighting, cooking, hot-water heating and heat-pump operation. When PV generated energy exceeds the house requirements, excess energy is directed back to the utility grid.

Detailed design illustrations are included in the report. Five appendices include specifications for power-conversion subsystems and for their installation, design tradeoffs, and models for performance simulation and economics.

Conclusions: The system presented provides a set of options expected to perform competitively in the Southeast in the mid-1980s to late 1980s.

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Photovoltaic Array Field Optimization and Modularity Study

George J. Naff

Objective: Develop fully integrated PV flat-plate array field subsystems that are optimized for low life-cycle energy costs for the intermediate-size application sector and identify and develop a modular PV array building block that, in multiple installations, can be used to implement large array fields with a minimum cost penalty over that for optimum designs.

Discussion: Existing array field designs were reviewed and evaluated. Design criteria and requirements to satisfy appropriate codes, safety, and equipment protection were then established. Design parameters that impact system efficiency were studied and their relationships determined. Twenty-kilowatt (kW), 100-kW, and 500-kW array field designs were configured. Finally, modularity methods for implementing the 20-kW, 100-kW, and 500-kW designs with minimally larger cost than for optimized designs were studied, leading to the final selection and design

of the modular building block. A low-cost structure/foundation is used, featuring a panel that is integral to the array structure and provides a self-grounding foundation. Power from each branch circuit is routed via buried cables to a power collection center.

Fifty-five figures and 18 tables are included. Eight appendices complement the main text.

Conclusions: Preferably, the building block is a plus-or-minus 200-volts-dc bipolar unit consisting of two 200-V monopolar subarrays, with a nominal power rating of 10-kW. The field is sectioned into 20-kW units with protection and controls provided for each field section. The life-cycle cost for a 100 kW field using the modular concept (excluding the cost of solar-cell modules) is estimated at less than \$100 per square meter in 1980 dollars.

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EMI from Solar Panels and Inverters

A Subcontract Report for Solar Energy Research Institute

Electromagnetic Fields Division,
National Engineering Laboratory,
National Bureau of Standards

Objective: To present results of measurements of electromagnetic interference (EMI), particularly at lower frequencies, caused by solar photovoltaic array and power conditioning systems.

Discussion: Radiated electromagnetic fields were measured near several solar array systems at the New Mexico Solar Energy Institute, Las Cruces, New Mexico, during September 1981. The measured results show that the inverters in these systems generate strong EMI, particularly at lower frequencies; e.g., in the AM broadcast band (0.5 to 1.6 MHz). The inverters generated most of the EMI in the solar-panel system. Measurements were made over the frequency range of 40 Hz to 600 MHz at distances from the inverters of 1, 10, 45, and 80 m. The levels of EMI at distances of 1 m were 50 dB above ambient at frequencies from 40 Hz to 1 MHz. At distances of 10 and 45 m, the levels

were 30 to 40 dB above ambient at frequencies from 40 Hz to 6 MHz. At 80-m distances, no signals were detected above ambient. Above 30 MHz, the EMI at a 1-m distance was at most no more than 5 dB above ambient.

Thirty figures are included.

Conclusions: If the filtering on inverters is improved, the radiated EMI could be reduced significantly. The EMI from the inverters in the measured system rendered the AM broadcast band useless at distances of 1 to 3 m and degraded the band within a 40-m radius. Television and FM broadcast reception, however, should not be bothered, but service on some of the lower frequency bands for amateur radio service is likely to be degraded.

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Issued January 1985

Extensive Modeled Terrestrial Solar Spectral Data Sets with Solar Cell Analysis

Richard E. Bird
Roland L. Hulstrom
Solar Energy Research Institute

Objective: To present solar spectral data sets in tabulated form, which can be employed for analysis in any solar technology where spectral effects are important.

Discussion: Experience has shown that a variety of accurate solar spectra are needed. The spectral code called BRITE has been updated with an improved extraterrestrial solar spectrum, a more accurate molecular scattering calculation, and other minor refinements.

Specific examples of the use of some of these spectra to determine the relative effect of global normal and direct normal irradiance on primary cell calibration procedures are presented for single crystalline silicon, amorphous silicon, gallium arsenide, and cadmium sulfide/copper sulfide.

The data sets illustrate the effect of air mass on both direct normal and global irradiance. In the direct normal mode, nearly complete extinction occurs in the ultraviolet (UV) end of the spectrum at large air masses; whereas in the global mode a significant

amount of UV radiation still penetrates the atmosphere. The infrared (IR) end of the spectrum is relatively unaffected by air mass in either the direct normal or the global mode.

For most of the materials examined here, air mass has a smaller effect on global normal cell calibrations than it does on direct normal cell calibrations; but turbidity, in many cases, appears to have a greater effect on direct normal cell calibrations than on global cell calibrations.

Conclusions: Agreement between a modeled spectrum and a measured spectrum over most of the spectral range between 0.3- and 2.3- μ m wavelength was obtained. These spectra will be valuable tools for many solar applications.

The results illustrated show that the cell calibration number is very sensitive to changes in the solar spectrum. This implies that cell efficiency measurements are probably very sensitive to spectral changes. As a result, poor quality spectral data or imprecise cell measurements can result in erroneous conclusions.

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Solar Report Summary

Issued June 1986

Report on High Intensity Solar Cells

R. J. Schwartz
J. L. Gray
M. S. Lundstrom

Objective: Present the results of research performed between February 1, 1981, and February 1, 1983, in an effort to develop high-efficiency, high-concentration, silicon solar cells at Sandia National Laboratories.

Discussion: Much effort has been directed toward the development of high-efficiency solar cells for terrestrial use. Significant progress has been made for their use as an alternative to more conventional energy sources. Silicon cells, in particular, are rapidly approaching theoretical limitations in efficiency. To help develop more efficient cells, a mathematical model would be invaluable. Solar cell geometries could be compared and optimized before actual fabrication, thus eliminating problems caused by the uncertainties of device processing. Since analytical models require too many simplifying assumptions, numerical models must be used; a two-dimensional model is needed because most solar cell geometries cannot be adequately handled in one dimension. This report addresses these concerns and presents the research conducted to approach them.

A primary goal of this research was to develop a computer code to model photovoltaic cells in two dimensions. The report describes the formulation of appropriate equations and boundary conditions to

model solar cells in two dimensions. The numerical method used to solve these equations is also presented. In addition, a description of the Solar Cell Analysis Program in 2 Dimensions (SCAP2D) is included. The results of SCAP1D (Solar Cell Analysis Program in 1 Dimension) and SCAP2D simulations of solar cells are compared. The report also presents the result of calculations using SCAP2D to analyze conditions that occur in solar cells operated under high intensities.

Thirty-seven figures accompany the text. Seven appendices are also included. The first four are papers concerning solar cells that were presented at various meetings and conventions. Appendix E describes the mobility models used in the research, and Appendix F describes the SCAP2D input deck. Appendix G presents a derivation for an effective surface recombination velocity.

Conclusions: Surface recombination at the illuminated surface of Interdigital Back-Contact (IBC) solar cells with charge-induced passivation can increase dramatically with solar concentration, reducing the high-intensity collection efficiency. A circulating current near the emitter contact under open-circuit conditions reduces the open-circuit voltage.

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Solar Report Summary

Issued June 1986

Development of a Second-Generation Linear Fresnel Lens Photovoltaic and Thermal (PVT) Concentrator Array, Including Fabrication and Installation of a 200 Square Meter Collector Field

Mark J. O'Neill

Objective: Present a summary of work performed under two Sandia National Laboratories, Albuquerque (SNLA) contracts to develop a new second-generation linear Fresnel lens photovoltaic and thermal (PVT) concentrator system, and to deploy a 200-m² collector field of the new design.

Discussion: This report summarizes the key results of two development contracts conducted by ENTECH, Inc. for SNLA. Under the first contract ENTECH developed a new second-generation linear Fresnel hybrid PVT array, and under the second contract ENTECH deployed a 200-m² field of the new second-generation PVT arrays at SNLA.

This report reviews previous module and array research before describing the second-generation array. Module and array development are discussed, and improvements and appropriate cost information are summarized. Prototype concentrator module designs developed during the study are presented, as well as prototype array systems. The 200-m² collector field is described in detail, focusing on field design, fabrication, and testing. Performance information is also included.

This publication contains 48 figures.

Conclusions: The following conclusions are presented:

- Second-generation linear Fresnel lens PVT collector modules have been developed with measured peak efficiency levels of 14.5% electrical and 47.5% thermal for a total of 62.0%.
- The new, second-generation modules incorporate several design improvements that result in a significantly lower manufacturing cost for the new module, despite its higher performance.
- The new arrays provide full two-axis tracking and inverted storage and can be integrated into long, interconnected rows.
- The mass-production economics of the second-generation PVT system should be excellent.
- Measured performance levels of the 200-m² collector field match predicted performance levels well.

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Solar Report Summary

Issued June 1986

High-Efficiency, Low-Cost, Passively-Cooled PV Concentrator Module

Neil Kaminar

Objective: Present research conducted to develop a high-concentration, high-efficiency gallium arsenide (GaAs) module using passive cooling.

Discussion: This publication presents the efforts of Varian, under contract to Sandia National Laboratories, Albuquerque, to develop an inexpensive, high-concentration, GaAs cell, passively-cooled concentrator module using plano-Fresnel lenses.

This detailed report describes all the stages involved in the development of this concentrator module. The design stage of the module is explained, including the role of computer models in the design. Outputs from a thermal model, an optical model, a cell model, and a cost model were combined to derive a lowest-cost-per-watt design. A description of the design optimization procedure employed is included, along with an overview of the module design. Fabrication processes are also presented, especially cell and lens fabrication, other secondary fabrication, and the assembly of the module itself. Testing performed on the module is described; component testing and module testing are discussed separately. The report also describes test

equipment, test procedures, and results of testing at Varian's Solid State Laboratory at Palo Alto, Calif., and at Sandia National Laboratories.

The text is accompanied by 103 figures. Two appendices are also presented: one describes the optimization procedure for the Gen-II module, and the other contains schematic drawings and technical information pertaining to the research.

Conclusions: This module program demonstrates the following three concepts:

- High-concentration modules can be built with standard plano-Fresnel lenses by using secondary concentrators. The modules have good flux distribution and good off-axis performance.
- High-concentration modules can be passively cooled effectively by using inexpensive components.
- Secondary concentrators dramatically improve the on- and off-track performance.

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Solar Report Summary

Issued December 1986

Conversion and Storage in Electrochemical Photovoltaic Cells: Final Report, 15 Sept. 1979 - 15 Jan. 1985 A Subcontract Report

M. Tomkiewicz
I. Ling
W. S. Parson
R. B. Silberstein
J. K. Lyden
P. Bratin
F. H. Pollak
W. Siripala
R. Garuthara
M. Hepel
W-M. Shen
B. Aurian-Blajeni

Objective: Provide a better understanding of the parameters that must be controlled to make efficient electrochemical photovoltaic cells with inexpensive in situ energy storage.

Discussion: The work for this report was done at the Department of Physics, Brooklyn College of the City University of New York, Brooklyn, New York, under subcontract to the Solar Energy Research Institute. During the early phase of the reported activity, the authors demonstrated that polycrystalline cadmium selenide (CdSe) photochemical photovoltaic solar cells (PEC) with AM1 efficiencies of approximately 6% can be reproduced. Thus, the emphasis of the study was shifted from attempts to optimize PEC further to the development of basic characterization techniques to aid understanding of the semiconductor-liquid interface in the PEC.

The report is a compilation of abstracts and reference lists of the 24 papers that were based on work done in

the study and were published in refereed journals. Preprints of papers that were submitted, but were unpublished when the report was written, are also included.

Conclusions: The research program at Brooklyn College served as a catalyst to increase interest in photoelectrochemical conversion systems. Undergraduate and graduate students and postdoctoral fellows, most of whom had no experience in photoelectrochemical or photovoltaic research, had the opportunity to work in a new scientific area. The authors believe that the single scientific highlight of their research is the demonstration that, in most cases, the abrupt junction approximation is not adequate to describe the semiconductor interface.

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Solar Report Summary

Issued December 1986

Objective: Develop and characterize hydrogenated amorphous silicon (a-Si:H) films and photovoltaic devices by chemical vapor deposition (CVD) from higher order silanes.

Discussion: This research project was conducted by Chronar Corporation, Princeton, New Jersey, under subcontract to the Solar Energy Research Institute. The motivation for the reported research was the prospect of using a new technique to prepare a-Si:H films having electronic properties similar or superior to those of material prepared by the traditional glow-discharge technique. Some of the possible advantages of thermal CVD over glow discharge are the absence of ion bombardment, high deposition rates, efficient use of feedstock gases, lower levels of

Photovoltaic Devices Using a-Si:H from Higher Order Silanes: Final Subcontract Report

A. E. Delahoy

impurity incorporation, absence of pinholes in the film, and improved material stability.

Following a brief discussion of the deposition methods used, the three major tasks in the program (1 — material preparation and analysis, 2 — comparative evaluation of various CVD techniques, and 3 — device fabrication and analysis) are described in detail. Eighteen figures and fifteen tables are included.

Conclusions: Flow CVD techniques produce higher device efficiencies than the static CVD method. The adoption of flow-deposition methods and the use of high-purity, silent-electronic-discharge (SED) disilane have led to substantial improvement of the electronic properties of a-Si:H prepared by CVD.

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Solar Report Summary

Issued December 1986

Studies of Chemical Vapor Deposition of Amorphous Silicon and Transparent Electrodes for Solar Cells: Final Report, 1 April 1983 - 30 September 1984

R. G. Gordon
S. Kurtz
J. Proscia
K. Gustin
J. Chapple-Sokol
D. Strickler

Objective: Investigate the potential for atmospheric pressure chemical vapor deposition (APCVD) for preparing hydrogenated amorphous silicon (a-Si:H) for use in thin-film solar cells and for preparing transparent conductive electrode layers.

Discussion: This report describes research performed at Harvard University under subcontract to the Solar Energy Research Institute. APCVD has recently emerged as a promising alternative to traditional amorphous silicon deposition methods. The lack of ion bombardment, high deposition rates, and the simplicity of the necessary technology indicate that the use of APCVD would lead to a sizable cost reduction in future large-scale manufacturing of amorphous silicon solar cells if successful.

In the reported project, a-Si:H was deposited using an improved CVD apparatus. Surface photovoltage collection lengths were measured, and the deposited material was analyzed for impurities. Titanium nitride films were produced and were tested for the resistance of the electrical contact between the film and tin oxide, as well as highly doped silicon. Silica and alumina films were prepared by APCVD and tested as sodium-

diffusion barriers to prevent degradation of solar cells by sodium diffusion from low-cost soda-lime glass. Titanium dioxide films prepared using APCVD were tested as oxygen barriers between tin-oxide-coated substrates and amorphous silicon subsequently deposited by APCVD. The properties of fluorine-doped tin oxide, a transparent conductor, were related to its fundamental electron-scattering mechanisms.

Three figures and four tables accompany the text.

Conclusions: Based on surface photovoltage collection lengths, intrinsic APCVD hydrogenated amorphous silicon films could be used in solar cells. Titanium nitride films produced by APCVD were found to provide a low electrical contact resistance to tin oxide and to highly doped silicon. Silica films were only partially effective as sodium barriers, but alumina films completely eliminated sodium migration from the glass substrate into deposited tin oxide. For fluorine-doped tin oxide, only minor improvements in conductivity and transparency may be expected from further optimization of deposition techniques.

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Solar Report Summary

Issued December 1986

Terrestrial Photovoltaic Power Systems with Sunlight Concentration Annual Progress Report — 1982-1983

C. E. Backus
R. W. Sanderson

Objective: Present research conducted on concentrator solar cells at Arizona State University from 1982 to 1983.

Discussion: Most of the U.S. photovoltaic program emphasizes silicon solar cells to lower the cost of flat-plate arrays. One option is optical concentrators that increase the concentration of sunlight onto the cells, reducing the area of cells required per unit of electrical output. This approach lowers the cost of electricity for photovoltaic systems significantly without requiring a large reduction in the actual cost of the cells since fewer arrays are needed. Investigation into this option has been under way at Arizona State University since 1970. This report presents research results from 1982 to 1983, but also includes a summary of research performed between 1974 and 1982.

One section describes concentrator cell testing. Cells from four different manufacturers were tested at irradiances as high as 1700 suns. Work on improving test procedures and techniques focuses on the problem of a changing outdoor spectrum affecting electrical-performance measurements on photovoltaic devices. The publication also describes the development of a spectral mismatch parameter to quantify the effects of using a reference cell that does not

match the test cell. A technique is explored for calibrating reference cells, which could result in greater calibration accuracy by eliminating the variability of the outdoor spectrum. Discussions of spectral response under high-irradiance and neutral-density filter measurements are presented. Graphic information of calibration number versus concentration data is displayed.

One table and five figures accompany the text. Appendix A consists of graphic representations of selected efficiency versus concentration curves. Appendix B presents spectral-response versus irradiance data in a graphic form. Appendix C lists the papers presented under this program. Appendix D is a list of research contributors.

Conclusions: Concentrator cells of various thicknesses, but otherwise identical processing, were tested. One-sun short-circuit current increased with thickness. Peak efficiency also increased with thickness, but high-irradiance performance was often better for thinner cells. Spectral-response measurements on concentrator cells under high irradiance indicate large superlinear effects on short-circuit current for high-base resistivity cells as irradiance was increased.

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Solar Report Summary

Issued December 1986

Objective: Develop accurate, predictive device models for III-V concentrator cells.

Discussion: Gallium arsenide (GaAs) was selected as a starting point to begin developing device models for III-V concentrator cells because GaAs is the most mature III-V concentrator-cell technology and GaAs solar cells have demonstrated high conversion efficiency. A one-dimensional solar cell simulation program (SCAPID), used at Purdue University since 1979, was modified for GaAs homojunction solar cell analysis by the installation of parameters for materials. The program can compute both dark and illuminated I-V and spectral-response characteristics, open-circuit voltage, short-circuit current, and conversion and collection efficiencies; the user can plot physical quantities over any segment of the device.

The publication contains a project overview that includes a review of device models and their performances. GaAs material properties and models are presented in detail, as are the materials for anti-reflection coatings and appropriate models. A comparison is also presented of the results taken from the one-dimensional computer-simulation program for GaAs and results taken from actual experimentation. A description of open-circuit voltage enhancement in graded-gap cells is included.

Three appendices accompany the report. They deal with the computer code described in the report, the

Theory of Advanced, High-Efficiency Concentrator Cells: Final Report

M. S. Lundstrom

R. J. Schwartz

C. M. Maziar

P. D. DeMoulin

graphic presentation of technical information, and a user's guide to the simulation program. Twenty tables and fifty figures are included.

Conclusions: Continued use of the model should help identify its weaknesses as well as provide insight into cell operation. The following conclusions result from the initial studies of this report:

- Illustrated results from SCAPID simulations of shallow homojunction cells (Fan and Bozler cell and the Borrego p-n cell) demonstrate successful comparisons with experimental work. Difficulties in modeling the spectral response of the cells are not unexpected given the limited knowledge of the optical properties of anti-reflective coatings.
- Modeling of the Sahai heteroface cell proved accurate although more comparisons between simulations and experimental data are needed.
- An examination of using a graded band gap to increase the open-circuit voltage of solar cells suggests that the most beneficial use of band-gap grading may be to enhance photocollection efficiency, not open-circuit voltage.

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Solar Report Summary

Issued April 1989

Objective: Develop a passively cooled, integral back plane (IBP) photovoltaic concentrator module with the cells bonded directly to the back plane of the module in order to eliminate the costs normally associated with ceramic insulators and copper heat spreaders.

Discussion: The research described in this report was conducted by the Varian Associates, Inc. in Palo Alto, California under subcontract to Sandia National Laboratories in Albuquerque, New Mexico. In the IBP design described, the functions of the ceramic insulator were replaced by anodizing the aluminum back plane and using a heat-conducting RTV silicone for bonding.

Several thermal cycle tests were performed on various RTVs and Eccosil Red 4952 RTV was selected because of its reported conductivity and demonstrated adhesive properties. A minimum thickness of 0.005 in. of RTV was required. The heat conductivity in the RTV is a significant determinant of the cell junction temperature and appears to be lower than advertised. An Eccosil S-11 primer was necessary for the RTV to function properly. When used with a primer, RTV is strong enough to be used to adhere cells, leads or heat spreaders without additional mechanical fasteners. RTV also has a low modulus of elasticity, allowing it to absorb repeated strains from temperature cycling.

Design of Point-Focus Back Panel Including Cell, Mounting, Encapsulant, and Interconnect

N. Kaminar

The prototype module utilizes a Varian trough module design, which consists of an aluminum panel bent into a trough shape. The lenses are bonded to the top of the trough and the cells are bonded to the bottom in a two-cell-wide arrangement. The trough has advantages such as simplicity of manufacture and assembly and structural economy. The module was mounted on Intersol trackers without requiring any modification to the tracker.

The report has more than 50 figures and tables and includes structural drawings of the module in an appendix.

Conclusions: The module structural design is strong and rigid. It could be made longer and with thinner sheet metal without exceeding maximum stress and strain values. This would lower its cost.

The best electrical standoff; i.e., isolation between cell and back plane of the various anodizations was 1500 volts, but this could be improved to over 2200 volts with the addition of silicone in the form of oil, grease or vulcanized rubber.

The module design is intrinsically inexpensive since there are few parts and they are easily made and assembled. RTV is expensive, although it is used in small quantities. With few changes, the installed cost of the array could be less than \$1.00 per watt, assuming high volume production and a DC bus.

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Solar Report Summary

Issued April 1989

Development of a 160X Crossed Lens Photovoltaic Concentrator

A. J. McDanal

Objective: Evaluate the performance and cost-effectiveness of a novel optical concentrator concept, called the crossed lens concentrator, that cross-couples simple plano-cylindrical lenses with a linear Fresnel lens.

Discussion: The research described in this report was conducted at the ENTECH, Inc. laboratories at the Dallas Ft. Worth Airport in Texas under subcontract to Sandia National Laboratories in Albuquerque, New Mexico. This report describes the design, analysis, and fabrication of a prototype crossed lens photovoltaic concentrator. The optical element of the module, the crossed lens, consists of a scalloped acrylic superstrate oriented perpendicular to a linear Fresnel lens. The scalloped acrylic superstrate contains multiple parallel plano-cylindrical lens elements on its outside surface. The linear Fresnel lens provides lateral focusing of the incident sunlight, while the plano-cylindrical lens elements provide longitudinal focusing. The system permits the concentration ratio to be increased from 40X to 160X, which reduces silicon cell area and costs dramatically.

The crossed lens module design is complete. Cost/performance tradeoff studies have resulted in design selections for all key elements in the module. These include the composite crossed lens, the

photovoltaic cell, the electrical interconnect, the copper heat spreader, and the finned aluminum heat sink. The report contains 26 figures and eight tables.

Conclusions: With typical current/voltage conditions, the prototype crossed lens concentrator module showed an operational electrical efficiency of 15.1%. This was in excellent comparison to the 15.5% value predicted by the optical/thermal/cell electrical model. The prototype had a composite lens efficiency slightly less than expected, but when superstrate problems are eliminated, a near-term crossed lens efficiency greater than 16% is expected. This compares favorably to state-of-the-art conversion efficiencies using silicon-cell-based technology.

Crossed lens concentrators offer excellent performance and cost savings compared to current linear Fresnel lens collectors. Although crossed lens module performance is exceptional, true performance potential has probably not been realized. Two design innovations are likely to boost peak module efficiencies above 20%. These are (1) a proprietary prismatic cell cover, which eliminates grid line obscuration and encapsulant front surface reflection losses, and (2) a proprietary 3M Company anti-reflection coating.

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Solar Report Summary

Issued April 1989

Dielectric Properties of Silicon Dioxide and Silicon-Oxynitride Sol/Gel Thin Films

L. A. Carman
C. G. Pantano

Objective: Assess the dielectric properties of silica sol/gel thin films and, in particular, their dependence upon thermal processing in ammonia.

Discussion: The research described in this report was carried out by the Department of Materials Science and Engineering, Pennsylvania State University, University Park, Pennsylvania, under subcontract to Sandia National Laboratories in Albuquerque, New Mexico. Sol/gel film coatings are considered candidate abrasion-resistant, and anti-reflection coatings for photovoltaic concentrator solar cells. This report is concerned with the electrical breakdown potential as a function of processing in ammonia.

There are three reasons for interest in the thermal treatment of silica sol/gel films in ammonia. First, 5-40 atomic percent nitrogen can be chemically incorporated and uniformly distributed in silica sol/gel films during thermal densification in ammonia at 900-1300°C. Second, this treatment is known to be an effective way to "anneal-out" the defects that limit the reliability of thin-film capacitors. Third, the (oxy)nitride structure can provide a more effective dielectric film material than the pure oxide in both passive and active applications.

The text is illustrated with seven figures, including two micrographs.

Conclusions: Silica sol/gel films in the thickness range 500-1000 Å exhibited relatively high leakage currents and low dielectric strengths when compared to the thermal oxide of silicon. The average dielectric strength was not measurably improved after the nitridation, although there were clear indications that the breakdown mechanism was influenced by the incorporation of nitrogen. The dielectric constant of the films was measured, and this verified that the ammonia treatment had effectively nitrided the silica structure.

The high leakage currents and low dielectric strengths reported are probably enhanced by the presence of pores, alkali impurities and interfacial defects in the film. Spectrochemical analyses of the sol/gel solutions, and SIMS depth profiles of the deposited films, verified the presence of sodium, potassium and boron impurities. Thus, the development of higher purity alkoxides, sols, and process environments will be required before the intrinsic electrical properties of sol/gel films are realized.

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Solar Report Summary

Issued April 1989

Objective: Develop the technology to fabricate an ultrathin AlGaAs solar top cell for a mechanical tandem stack with silicon bottom cells that is 17% efficient at 400 suns, has a bandgap of 1.7 eV, and is transparent to sub-bandgap photons.

Discussion: The research described in this report was conducted at the SPIRE Corporation in Bedford, Massachusetts under a subcontract to Sandia National Laboratories in Albuquerque, New Mexico. The unique aspect of the work reported here is the MOCVD growth of the AlGaAs cell on a germanium substrate, subsequently completely removed by selective etching.

Cell designs were completed for both GaAs and AlGaAs cells. The cell structure was a conventional p-on-n heteroface design. A grid pattern, optimized for 500 suns operation, was designed and photomasks were generated. A tantalum pentoxide antireflection coating was designed for optimum efficiency in conjunction with the AlGaAs window layer.

GaAs solar cells were fabricated on both Ge and GaAs substrates. GaAs concentrator cells with an efficiency of 19% were obtained. The formation of an unintentional p-n junction in the Ge substrate during GaAs cell growth was a problem in using Ge substrates. The problem was solved by removing the Ge substrate, but the best efficiency obtained for a GaAs cell on a Ge substrate at one sun was 16.4%. AlGaAs solar cells were also fabricated on Ge and GaAs substrates.

Development of a Thin AlGaAs Solar Cell

SPIRE Corporation

1.69 eV AlGaAs concentrator cells were obtained that had an efficiency of 13.7% at 242 suns.

Processing procedures for superstrate attachment, substrate removal, back ohmic contact grid formation, and back antireflection coating were developed. A thin (5 micron) GaAs cell was fabricated that had parallel finger grid patterns on both sides and was transparent to below-bandgap light. A thin AlGaAs cell was also produced that demonstrated the complete process, with concentrator cell grid patterns and antireflection coating on both sides of the 5-micron cell.

Conclusions: The following conclusions were reached:

- Removable Ge growth substrates are a viable approach for producing ultrathin solar cells of GaAs and AlGaAs.
- Doping of the active cell layers by Ge during growth can be controlled effectively by capping the backs of the Ge wafers with epitaxial GaAs.
- Diffusion of Ga and As into the substrate produces a Ge p-n junction in series with the active solar cell.
- Selective etching with hydrogen peroxide is an effective way of removing the Ge substrate without harming an ultrathin 5-micron solar cell.
- Thin solar cells of AlGaAs and GaAs have been produced with little or no degradation of starting efficiency.

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Solar Report Summary

Issued April 1989

Design and Development of Laminated Fresnel Lens Parquet for Point-Focus Photovoltaic Systems

B. Baum
W. H. Holley
J. P. Galica
L. A. Thoma

Objective: Develop an adhesive and bonding mechanism capable of fabricating laminated Fresnel lens parquet (5x6 in. lens) molded out of polymethylmethacrylate (PMMA) resin or "acrylic" that would survive outdoor weathering for at least 20 years without significant degradation.

Discussion: The research described in this report was performed at Springborn Laboratories, Inc. in Enfield, Connecticut under subcontract to Sandia National Laboratories. Of all the adhesives evaluated, silicone and ethylene vinyl acetate (EVA) copolymer were best suited for bonding glass to acrylic lenses. In both of these laminate systems, the acrylic was annealed and flamed and then both glass and acrylic substrates were primed before laminate construction, in order to obtain a sufficiently strong bond.

Based on the desired properties of high light transmission and successful weathering and aging, the RTV-615 silicone laminate system from General Electric Company was initially determined to be the most promising system for this application. Each lot of adhesive RTV-615 obtained from the manufacturer was variable and, hence, unreliable. Three additional silicone elastomers were evaluated as alternatives, but none was as successful as the original RTV-615. Three optically clear silicone gels were also evaluated as adhesives, but the gels exhibited delamination and fingering upon testing.

EVA systems do not compare as favorably as the silicones in light transmission and thermal cycling;

however, the substantially lower cost of EVA adhesives makes them a viable alternative. When the adhesive is in sheet form, long-term storage and easy handling during fabrication are advantages. Attempts to construct adhesive systems based on combinations of silicone and EVA composite adhesives were moderately successful. The principal advantage of such a composite system is an 80% reduction in cost compared to silicone alone. EVA bonds well to primed glass, whereas silicone bonds well to primed acrylic.

The report contains 22 tables and seven appendices.

Conclusions: Further development is necessary to optimize the characteristics of these systems. The report recommends that the following actions be taken:

- After laminate construction, anneal the entire assembly to relieve internal stress that may induce delamination.
- Continue to develop composite silicone/EVA laminates, varying the relative adhesive thicknesses.
- Investigate silicone gels as laminate adhesives. Try mechanically clamping the acrylic to glass contact to contain the gel.
- Investigate precured silicone inserts mechanically clamped between the glass and acrylic substrates.
- Investigate the feasibility of alloying EVA and silicones, or other transparent elastomers, for adhesive optimization.

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Solar Report Summary

Issued April 1989

Objective: Design and develop a cost-effective Fresnel lens, with an efficiency of at least 80%, for use in point-focus photovoltaic systems.

Discussion: The work described in this report was carried out at the American Optical Corporation in Southbridge, Massachusetts under a subcontract to Sandia National Laboratories. Injection molding is an attractive alternative to compression molding as a lens fabrication process since high yields and low labor costs associated with the technique can substantially reduce the cost of lens manufacturing.

The research described in this report was divided into two phases. In the first phase, a mold insert was fabricated to an existing optical design and used to define process parameters and capabilities. In the second phase, a new optical design was developed that was optimized for injection molding and another mold insert was fabricated. The latter insert was used to mold parts for final testing and comparison.

Three major categories of efficiency loss were identified: (1) tool fabrication, (2) molding process, and (3) lens design. Efficiency losses in tool fabrication were attributed to facet alignment, resolution of peak and valley radii, and surface quality. The basic causes of efficiency losses in the molding process were requirements for draft angles and tip and valley radii and warpage. Optical design criteria are constrained by tooling and molding necessities, specifically min-

Design and Development of Injection Molded Fresnel Lenses for Point-Focus Photovoltaic Systems

C. L. Grendol

imizing the effects of peak and valley radii and draft angle.

Twenty-seven figures and two tables accompany the text. An appendix, "Lens Image Profile Data," is included.

Conclusions: An optimized optical design was developed and lenses were fabricated from this design. The lenses had an average tested efficiency of 79.3%, compared to the unoptimized average efficiency of 68.5%. Further optimization of the molding process by installing a vacuum system to draw on the injection cavity prior to molding increased the optimized average efficiency to 81.6%.

Several important factors led to the development of injection molded Fresnel lenses with efficiencies of 80%:

- The optimal optical design uses a curved facet design that minimizes the number of facets.
- A mold design must be developed to give even flow, minimal molded-in stress, and uniform ejection to prevent warping.
- The optimal material must be chosen for cleanliness, molding characteristics, and optical clarity.
- Creating a vacuum inside the mold cavity enables the material to follow the contours of the mold more closely and improves the overall clarity of the lens.

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Solar Report Summary

Issued April 1989

High-Efficiency Silicon Concentrator Solar Cells

M. A. Green
A. W. Blakers
Z. Jianhua
M. Taouk
S. Narayanan
P. Campbell

Objective: Apply non-concentrating silicon solar cell technology to concentrator cells and obtain 22% efficiency with low resistivity substrates.

Discussion: This research was carried out at the University of New South Wales in Kensington, Australia under subcontract to Sandia National Laboratories in Albuquerque, New Mexico. The original efficiency targets of the project were comfortably exceeded, with efficiencies as high as 24.7% demonstrated in the 50-100 suns concentration range for small area, low resistivity cells. Furthermore, the authors were able to demonstrate 22% efficiency for concentration ratios in the 1-500 suns range and 20% efficiencies up to 1000 suns. These results represent significant improvement over levels previously established for low resistivity substrates, although they are overshadowed by recent efficiencies for high resistivity substrates.

The report also describes experiments designed to passivate p-type surfaces as a prerequisite for demonstrating similar high efficiencies for high resistivity substrates. Using low resistivity n-type substrates, the p-type top surface was sufficiently well passivated to produce one-sun open-circuit voltages up to 665 mV at 28°C. Applying the improved surface passivation capability to high resistivity substrates did not produce the performance levels sought. Compared to the target of 660 mV on high resistivity substrates, the highest value obtained was 636 mV at

28°C for a high resistivity p-type substrate with a phosphorous-doped top junction and an aluminum-diffused rear junction.

A third section of the report describes theoretical and experimental investigations of light-trapping schemes applied to concentrating cells, particularly those based on pyramidal texturing and grooving of one or more surfaces. Structures are described that maintain superior performance to Lambertian surface randomizing schemes, particularly for light incident within a range of angles centered about the perpendicular to the cell surface, the normal situation for concentrator cells.

Conclusions: Improvements in low resistivity silicon concentrating cells can be applicable immediately in fabricating cell modules. Cells of 1 cm active region diameter were designed and fabricated using the improvements described in this report. These cells displayed efficiencies up to 23.3% at the design ratio of 150 suns in a Sandia 200X experimental module. This efficiency is consistent with the design goal of 20% efficiency at the module level.

To approach the limiting performance of silicon concentrator cells, it is necessary to take advantage of enhanced light trapping schemes. Prismatic covers offer the best near-term prospect of the light-enhancing schemes studied, although geometric schemes with structure on both surfaces also have potential.

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Process Heat

Many solar technologies can have important applications for industry and agriculture. About 25 percent of the energy used in the United States is consumed by processes such as steam heating, crop drying, cooking, harvesting, and other tasks. These processes now require costly natural gas, oil, and electricity, but existing solar technologies can be applied to do the same thing. The specific solar technology used depends on the exact process and is usually determined by temperature.

Biomass energy systems are some of the most versatile methods that can be used to meet all ranges of temperatures. For example, heat to dry grain can be produced by burning crop wastes. And digesters, which convert animal waste into gas, provide fuel for a variety of agricultural uses. Gasohol, a mixture of 10 percent ethanol and 90 percent gasoline, can be burned in any gasoline-fired internal combustion engine and, therefore, has virtually unlimited uses in both industry and agriculture.

Many industrial and agricultural tasks can be accomplished with low-temperatures (below 177°C, 350°F) by using flat plate collectors or shallow

ponds. Even passive solar techniques will work for such uses as heating and cooling livestock shelters.

Solar energy is most cost-effective at low and intermediate temperatures, and agricultural energy needs are concentrated in this range. At least 27 percent of total industrial process heat needs fall here also.

Applications in the intermediate temperature range (177-315°C, 350-600°F) can be met with solar equipment such as evacuated tube collectors or linear focusing concentrating collectors which track the sun on a single plane.

However, some 60 percent of industrial process heat demand is in the high-temperature range (over 315°C, 600°F) for steel making, oil refining, cement and glass manufacturing, and chemical production. Solar technology can achieve these temperatures with fully tracking parabolic collectors, biomass pyrolysis, and other advanced systems.

SERI Report Summary

SERAPH Implementation Plans

Jim Castle
Wen Su
Douglas A. Dougherty
John D. Wright

Objective: Describe the work done in planning the design, construction, and operation of the Solar Energy Research and Applications in Process Heat (SERAPH) facility at SERI.

Discussion: The SERAPH experimental facility at SERI will provide the capability of addressing many of the technical issues facing industrial thermal energy system development and implementation.

As discussed in the report, the primary building blocks of SERAPH are the solar energy delivery subsystem, control and data acquisition subsystem,

energy distribution subsystem, and areas for storage development and introduction of load devices. Detailed descriptions are given for all these aspects of the SERAPH facility.

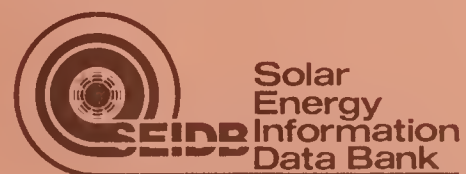
Seventeen figures and two tables accompany the text.

Conclusions: The SERAPH in-house experimental facility will provide SERI with a flexible tool for engineering and research activities aimed toward implementation of solar thermal technology to meet the process heat requirements of U.S. industry.

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SERI Report Summary

Solar Energy and the Oil Refining Industry

E. Kenneth May

Objective: Investigate the potential of solar thermal technology to provide industrial process heat (IPH) to the oil refining industry.

Discussion: The petroleum refining industry consumes energy equivalent to 11% of the energy content of the crude oil processed. Natural gas and fuel oil account for 4% of the energy used. About 80% of the total energy is to provide process heat.

From a survey of the process heat requirements of the major petroleum refinery processes, it is determined that 22% of the refinery process heat is consumed at temperatures below 288° C (550° F), and 62.5% is consumed between 288° C and 593° C (550° F to 1100° F). Technological constraints are shown to preclude the displacement of natural gas and fuel oil to five processes operating in excess of 371° C (700° F). However, alternatives such as coal and solar energy could provide process heat below 371° C (700° F). Temperatures below 371° C comprise about 25% of IPH use. The feasibility of these energy sources as well as the impact of conservation is discussed in the report.

Two figures and 11 tables supplement the text.

Conclusions:

- The potential for fuel displacement in refineries is about 40 percent of the total energy requirements, made up of about 28 percent natural gas and 12 percent fuel oil.
- Previous industrial process heat studies have overemphasized high temperature requirements.
- No technically feasible alternative to conventional liquid fuels for process heating to temperatures above 371° C (700° F) is expected in the near future.
- Solar energy has little potential for supplying process heat in the temperature range of 371° to 593° C (700° to 1100° F).
- Either coal or solar energy could be used to supply low-temperature heat requirements below 371° C (700° F).
- The primary obstacle to the use of coal is environmental, although the cost of installing coal-

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burning equipment can be up to eight times the cost of gas- or oil-burning facilities.

- A central-receiver solar energy system without storage, sized to deliver a maximum of 25 percent of process heat requirements, could

displace about 4.1 percent of a refinery's fuel needs.

- A central-receiver facility without storage, which could supply the maximum potential quantity of solar energy to a 100,000 barrel-per-day refinery, would occupy about 240 acres.

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SERI Report Summary

Preliminary Operational Results of the Low-Temperature Solar Industrial Process Heat Field Tests

Charles F. Kutscher
Roger L. Davenport

Objective: Summarize and analyze the cost and performance data from six industrial process heat (IPH) field tests funded by the U.S. Department of Energy.

Discussion: The subject field tests have all been in operation for at least a year. They are all low-temperature projects, supplying IPH at temperatures below 100°C (212°F). During the 1979 calendar year, SERI personnel visited all of the field tests to obtain performance and cost data. Contractors were interviewed about their project experiences. The six field tests included three hot water and three hot air systems.

Performance data from the field tests were analyzed in terms of system utilization, collector and system efficiencies, and parasitic power consumption. Actual costs were reduced to dollars per

square foot of collector and dollars per million Btu delivered annually by the respective system.

Eight figures and six tables complement the text.

Conclusions: Collector array efficiencies ranged from 12 percent to 36 percent with net system efficiencies from eight percent to 33 percent. Excluding design and data acquisition costs, the costs of the projects ranged from \$25 to \$87 per square foot and from \$499 to \$1537 per million Btu delivered annually.

Problems encountered in the tests included industrial effluents on collector surfaces, glazing and absorber surface failures, excessive thermal losses, freezing and overheating, control problems, and data acquisition system failures.

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SERI Report Summary

Applications and Systems Studies for Solar Industrial Process Heat

Kenneth C. Brown

Objective: Summarize the results of SERI work in systems analysis, economic analysis, and applications studies for solar thermal industrial process heat.

Discussion: SERI initiated efforts in applications and systems studies for solar industrial process heat (IPH) in early 1978. This report highlights some of the important aspects of the industrial systems and applications study program. The work completed during fiscal years 1978 and 1979 is reviewed and the program of study for fiscal year 1980 is presented. In addition, the report includes a summary of issues that should be addressed by SERI in the future.

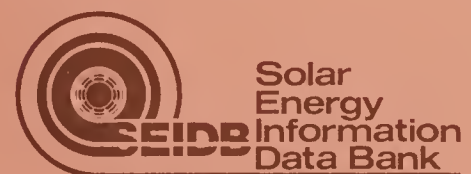
Conclusions: The applications and systems study program has introduced two important new concepts. First, it is clear that the national program in solar energy must turn toward future patterns of energy use, instead of focusing on various versions of the present scenario. Second, an overall approach to industrial energy use must be emphasized. An engineer wants the best solution to his problem, free from programmatic boundaries or technologically biased analyses.

These two concepts define the direction of future SERI programs in systems analysis for industrial solar energy.

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SERI Report Summary

Industrial Process Heat Case Studies

Douglas W. Hooker
E. Kenneth May
Ronald E. West

Objective: Describe the results of investigations into potential solar industrial process heat (IPH) applications.

Discussion: The IPH case study program was formulated to provide the detailed information needed for an accurate assessment of solar IPH potential in selected industries. Factors considered in the case studies include energy conservation alternatives, reconfiguration of industrial processes for energy conservation or enhancement of solar applications, land availability, the capability of providing solar energy at the required temperatures, and the possibility of using solar preheating for process streams. The overall objectives of the IPH case study program are:

- to determine the near-term feasibility of solar IPH for selected industries using currently available technology;
- to identify energy conservation measures and energy-saving process modifications;
- to identify features of IPH systems that affect the potential use of solar energy;
- to test SERI's IPH analysis software, PROSYS/ECONMAT (Process Heat Systems Model/Economic Matching);
- to disseminate solar information to the industrial community; and

- to provide input and guidance to the SERI research program.

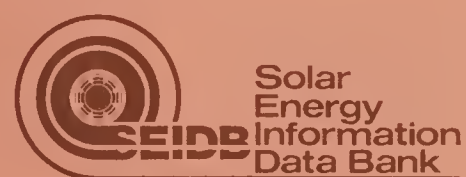
The results of seven IPH case studies are presented in this report. Individual plants in the following industries were studied: crude oil production, aluminum container manufacturing, corn wet milling, polymeric resin manufacturing, fluid milk processing, baking, and meat processing. For each process that was examined, the PROSYS software was used to simulate the average annual performance of the solar system most suited for the application. The ECONMAT software then determined the cost effectiveness of the solar system compared to the conventional fuel source currently being used in the process.

Five appendices present details of the software, methods, and data used in the studies. Thirty-five figures and 26 tables are included.

Conclusions:

- For the seven plants studied, few solar applications were found that are economical in the near term. The few potentially attractive solar applications that were identified resulted from unusual circumstances in the individual IPH applications, such as very expensive or inefficiently used conventional fuel sources, or

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from solar system designs that were able to displace more fossil fuel gross energy value than was actually supplied by the solar system.

- Four categories of factors were identified that favor the application of solar IPH systems: environmental, process, economic,

and company-related. Each category is presented in detail in the report.

- The increased cost of conventional fuels and the trend toward energy conservation could foster solar IPH applications in the near term.
- The PROSYS/ECONMAT computer codes are useful tools for such case studies.

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SERI Report Summary

SERAPH Facility Capabilities

James Castle
Wen Su

Objective: Provide a detailed description of the SERAPH (Solar Energy Research and Applications in Process Heat) facility to be constructed at the Solar Energy Research Institute field test site near Golden, Colo.

Discussion: Replicating industrial design assembly, procurement, and operational procedures, the SERAPH facility will test a series of solar heat systems to determine which can

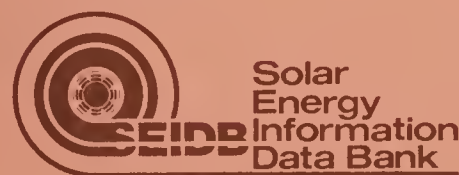
reliably meet load demands for low- and mid-temperature process heat. SERAPH management will invite observers and publish technical results.

Conclusions: The SERAPH facility will study the application of solar system technologies to industrial needs, expand engineers' and designers' knowledge of system behavior, and encourage industry acceptance of solar technology through dissemination of research data.

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Solar Report Summary

Issued November 1982

Design Considerations for Solar Industrial Process Heat Systems

Nontracking and Line Focus Collector Technologies

Charles F. Kutscher, Editor

Objective: Provide design recommendations based on information obtained from the design and operation of the U.S. Department of Energy (DOE) solar industrial process heat field tests.

Discussion: Since 1977, DOE has funded a series of solar industrial process heat field tests. This document lists the projects involved, and presents design recommendations based on information obtained from the tests to aid the designers of new systems. The report lists items that should be considered in each aspect of design of a solar industrial process heat system. The collector technologies covered are flat-plate, evacuated tube, and line focus, since these systems have been employed in the DOE field tests. A glossary of technical terms is included for the designer lacking solar system experience. Qualitative design considerations are stressed, rather than specific design rules.

Eleven figures and eight tables are included. Appendix A is a list of sources of information for the interested designer. Problems unique to solar industrial process heat systems (e.g., industrial effluents and overnight losses) are discussed as well.

Conclusions: Many of the problems experienced in the solar industrial process heat field test program occurred in earlier government programs that demonstrated the use of solar energy to supply domestic hot water, space heating, and cooling for buildings. Those problems included freeze damage of a heat exchanger due to thermosiphon heat loss in a collector loop and breakage of evacuated tube collectors due to thermal shock. The design considerations presented in this document should help prevent such mistakes in the future.

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Solar Report Summary

Issued November 1982

A Geographic Market Suitability Analysis for Low- and Intermediate- Temperature Solar IPH Systems

A. Keith Turner
Joseph C. Weber
Michael DeAngelis

Objective: Present the results of a geographic market suitability analysis for solar industrial process heat (IPH) systems.

Discussion: Previous studies of the industrial market for solar energy systems have considered the level of solar radiation as the main determinant of geographic markets in the U.S. This study evaluates geographic markets using such criteria as output of different types of low- and intermediate-temperature solar thermal collectors, air quality constraints for competitive fuels, state solar tax incentives, fuel costs, low-temperature industrial use of coal, high industrial growth areas, and industry energy consumption in different parts of the U.S. Market suitability analysis and mapping techniques, refined over the past 20 years by land-use planners, were used to evaluate geographic markets. A computer-aided system "Generalized Map Analysis Planning System" (GMAPS) performed interactive, cellular computer mapping, and composite mapping.

Twenty-one separate maps were produced from data and analyses based on the above criteria. Composite maps were then produced by GMAPS by combining the 21 maps into logical groupings of supply, competitive fuels, and demand. Matching the groupings to

the output maps for different types of collectors produced the final geographic "suitability" maps.

Volume I contains the study results. Twenty-two figures and 46 tables are included in Volume I, as well as the complete set of maps produced in the study. Volume I also contains an executive summary.

Volume II is comprised of eight appendices which present the graphic analysis methodology; descriptions of data sources, selection, and analysis; estimates of solar collector system outputs; and information on related tax regulations and incentives. Volume II contains seven figures and 33 tables.

Conclusions: The study results indicate that the U.S. Southwest and West are the most attractive geographic markets for solar IPH, based on equal weighting of the evaluation criteria. The West North-Central and East South-Central regions appear to have the least attractive markets. However, when different weights are assigned to the various criteria, the results change significantly for some regions of the country, such as New England, the Mid-Atlantic and the West South-Central regions. The results of this work will become less valid in the future as state incentives for solar IPH, air quality regulations, and the status of competitive fuels change.

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Solar Report Summary

Issued November 1982

Solar Industrial Process Heat — A Study of Applications and Attitudes Final Report

Vickie Wilson
Insights West

Objective: Provide data on decision makers' attitudes toward, and applications for, solar thermal techniques.

Discussion: One hundred meetings were held with industrial plant executives to yield information on the technical, economic, and attitudinal issues affecting industry's near-term (within five to seven years) market acceptance of solar thermal technologies. The study was designed to complement an earlier survey by the Gas Research Institute (GRI). The present study included fourteen Standard Industrial Classifications, including nine which were covered by the GRI survey. Plants included in the study were spread over 31 states, emphasizing areas with high insolation rates and a moderate-to-high industrial base.

Three figures and ten tables are included. Appendix A is an example of the interview format followed. Appendix B presents the quantitative procedure used to rank "suitability" of applications to solar energy.

Appendix C is a computerized listing of the interview data.

Conclusions: The study data suggest several possible near-term market opportunities for solar thermal energy systems. Plants using electricity as the primary fuel for industrial process heat appear to be attractive early-entry markets for solar energy, due to their present high fuel costs. Additional opportunities exist in plants that have accomplished much of their conservation plans, or that have a significant fraction of their operating budgets committed to energy expenses. The suitability analysis identified eleven industrial plants as "highly suitable" for solar thermal applications; they included producers of fluid milk, pottery, canned and bottled soft drinks, fabricated structural metal, refined petroleum, aluminum cans, chrome and nickel plating, and stamped frame metal and metal finishings.

The study indicates that the information available to industry on solar thermal technologies is inadequate.

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Solar Report Summary

Issued November 1982

Thermal and Economic Analysis of Solar-Assisted Heat Pumps for Low- Temperature IPH Applications

Sushil K. Chaturvedi
L. M. Murphy

Objective: Determine the potential technical and economic merits of solar-assisted heat pump (SAHP) systems for low-temperature industrial process heat (IPH) applications.

Discussion: The industrial sector is widely recognized as the largest energy user in the economy of the United States. In 1977, the industrial sector accounted for 37 percent of the total U.S. energy consumption. Sixty-eight percent of this industrial energy requirement is in the form of process heat, hot water, steam, and hot air.

The SAHP chosen for this IPH comparison study is a water-to-water heat pump system with an unstratified storage tank, backed up with a 100 percent conventional auxiliary system. The solar assist was assumed to be provided by flat-plate solar collectors. The SAHP system was compared on a thermal and economic performance basis with both flat-plate and parabolic trough, stand-alone solar systems. The baseline heat pump was assumed to be an eight kilowatt (thermal) system with specifications from a commercially available unit. The sensitivity of the results to variations in heat pump rating as well as storage capacity was determined. The performance was compared for two locations: Denver, Colo. and El Paso, Tex. The thermal performance of the various systems was predicted

by combining design techniques for the solar input and the performance of the heat pump system for that input.

The predicted thermal performance of the system was used together with the economic analysis procedure developed to study end-use matching of IPH systems. A cost of several solar-based, financial and economic parameters, including the initial investment, the rate of return, corporate tax rate, interest on capital, the life of the system, and inflation rate, was then calculated, and the systems were then compared.

Seventeen figures and two tables are included. Seven appendices present details of the analysis.

Conclusions: The SAHP system considered appears to be the most promising of the three solar options for the Denver location, and its delivered energy cost is within ten percent of that of the parabolic collector energy cost for El Paso. The solar SAHP systems look more promising as the weather becomes more severe.

Issues that need further study include the optimization of the collector system, both with and without the heat pump; the consideration of low-cost collectors and salt ponds; the inclusion of stratified storage; and larger heat pump sizes.

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Solar Report Summary

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Design Approaches for Solar Industrial Process Heat Systems

Nontracking and Line-Focus Collector Technologies

Charles F. Kutscher
Roger L. Davenport
Douglas A. Dougherty
Randy C. Gee
P. Michael Masterson
E. Kenneth May

Objective: Provide a handbook for the design of solar industrial process heat systems.

Discussion: The contents of this handbook have been arranged to guide the user through a system design. The first part, "Objectives and Fundamentals," provides an introduction to the uses of solar thermal energy in industry. It is intended for those who do not have experience in the solar IPH field, but it could also serve as a useful review. The second part, "Conceptual Design," describes how to choose the proper application and system configuration and how to estimate the amount of energy the solar system can be expected to supply. The conceptual design should supply enough information to allow the user to make an informed decision about whether to proceed with

the project, and it will also provide a firm foundation for further design work. The third section, "Preliminary Design," describes how to select and optimize system components. This section also explains how to determine the delivered energy more accurately. A chapter on installation and start-up is included. Items of special interest are covered in the appendices, and a glossary is provided for those new to the solar energy field.

One hundred figures and 39 tables are included.

Conclusions: This handbook should be a valuable tool for designers and planners involved in development of solar industrial process heat systems.

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Solar Report Summary

Issued November 1982

Preliminary Operational Results of the Low- Temperature Solar Industrial Process Heat Field Tests

Charles F. Kutscher
Roger L. Davenport

Objective: Present revised and new performance results from seven solar industrial process heat (IPH) field tests.

Discussion: Seven IPH field tests, funded by the U.S. Department of Energy, have been in operation for one year or longer. Three of the systems are hot water systems, and four are hot air systems. All are low-temperature projects that supply process heat at temperatures below 100C (212F). Flat-plate, evacuated-tube, and linefocus collectors are all represented in the program.

The original version of this report was published in June, 1980. At that time, only six of the seven projects

were covered. The Gilroy Foods, Inc., system became operational too late for inclusion in that report. This edition contains a discussion of the seventh project, as well as updated information on the other six.

Nine figures and seven tables are included.

Conclusions: The seven projects can be characterized as successfully delivering process heat to industry, although generally at subpar performance levels due to design inadequacies or operational difficulties. Problems encountered have included industrial effluents on collectors, glazing and absorber surface failures, excessive thermal losses, leaks, freezing and overheating, and control problems.

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Solar Thermal Power

Solar thermal energy systems utilize concentrating mirror/lens solar energy collection technologies for generation of heat and possible conversion to electricity or shaft power. The technologies which use collectors or reflectors to track the sun, encompass three broad areas: *point focus*, *line focus*, and *central receiver systems*. These technologies allow generation of heat energy ranging from ambient temperature to 2000°C (3632°F).

Point focus systems, with temperature capabilities up to 2000°C (3632°F), concentrate the solar flux incident on a parabolic mirror onto a receiver which converts the concentrated flux to heat energy. Point focus systems can be used singly (up to 75 KWe) or in arrays depending on the application desired. In a line focus system, the collector is one or more mirrored parabolic troughs which concentrate the solar flux on a line receiver at the focus of the parabola. A working fluid flows through the receiver. This heated fluid, generally up to 300°C (572°F) is used for the specific application of the system.

A central receiver system consists of a tower surrounded by a field of tracking mirrors called heliostats which direct and concentrate the sun's rays to a receiver mounted on the tower. This type of system is capable of producing large quantities of power, with initial systems in the range of 10 - 300 MWe.

There are currently four general applications for solar thermal systems:

- **Electric Power Generation** - The heated fluid (gas or liquid) is transferred from the receiver to a turbine which runs a generator. The electricity produced can be used at or near the site where it is generated, or it can be fed into the electric grid system.
- **Industrial Process Heat** - The heat in the receiver is transferred via a working fluid to locations in a factory where process heat is required. Industrial requirements for process heat are very large and run from relatively low to high temperatures.
- **Fuels and Chemicals** - Many endothermic chemical processes (process which requires heat) can be performed inside a solar thermal receiver serving as a chemical reactor, eliminating the need to transport the heat produced elsewhere. Production of fuels and chemicals using this approach has tremendous potential as an application of solar thermal power.
- **Total Energy Systems** - In a total energy system, the high temperature fluid produced in the receiver is used to generate electricity. After running the turbine the lower temperature (but still hot) fluid is used for space heating, hot water heating or for process heat. Also low temperature electrical machinery could be operated with reject heat from an industrial process.

SERI Report Summary

Survey of Solar Thermal Test Facilities

Keith Masterson

Objective: Describe the facilities currently available for testing solar thermal energy collection and conversion systems.

Discussion: This report surveys U.S. solar thermal test facilities and some foreign high-temperature test facilities that will play important roles in developing solar thermal systems. Although the emphasis is on mid- and high-temperature technologies using concentrating collectors, a brief list of facilities which test flat-plate collectors is also included. A 1975 survey of facilities by the Aerospace Corporation is frequently referenced.

The present Department of Energy (DOE) program requirements for concentrating collector technology and its supporting test needs are reviewed. Ten facilities, mostly located at national laboratories, either already exist or are planned to support the distributed concentrating collector program.

Test requirements for central receiver technology are also identified—three existing facilities and

one planned domestic facility provide support for this technology for the near future. The five-megawatt (thermal) Central Receiver Test Facility at Albuquerque, N.M., and the 400-kilowatt Advanced Components Test Facility at Atlanta, Ga., are the principal installations discussed.

Appendices containing specific data on each facility discussed as well as a reprint of the 1975 Aerospace Corporation survey are included in the report. Four tables and one figure complement the text.

Conclusions: Seventeen facilities within the U.S. have capabilities for testing nonconcentrating collectors. Most of those can meet the requirements of the American Society for Heating, Refrigeration, and Air Conditioning Resolution 93-77. In view of the needs of the DOE program, it is recommended that all but one of the test facilities receive continued support. Since test facilities for central receiver technology are expensive, additional large installations cannot be justified at this time.

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SERI Report Summary

Thermal Energy Storage for Solar Applications: An Overview

Charles Wyman

Objective: Present a current overview and assessment of the status of thermal energy storage technologies for solar applications.

Discussion: This report presents an overview of current technology and programs including some economic studies in low, intermediate, and high temperature thermal energy storage for solar applications and an assessment of key problem areas. Previous studies of the economic role of storage for home heating and stand-alone electric plants are examined first, and the factors which affect the economics of storage are discussed. Next, the costs and storage capacities of representative sensible and latent heat storage materials are summarized. Various modes of operation are also presented for thermal storage by reversible chemical reactions, but this technology is at such an immature stage of development that its economic and technical potential are not clearly understood. Some new ideas in containers and heat exchangers are reviewed to illustrate possible innovations in reducing storage costs. A more detailed examination is then made of reversible reaction storage, and gas-solid reactions are shown to have desirable characteristics for solar energy storage. However, there are problems with heat and mass transfer and heat ex-

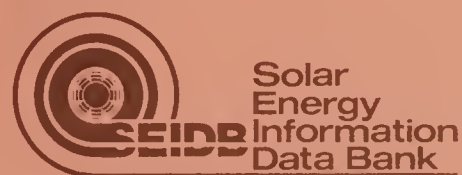
change for these systems that must be solved to make such systems more economically attractive. The Department of Energy (DOE) programs in thermal energy storage are reviewed in light of this discussion, and recommendations are made for future program directions which appear to have the greatest potential impact on reducing technical and economic barriers to solar applications of thermal storage.

Forty-three figures complement the text.

Conclusions:

- The greatest need in sensible heat storage is to minimize the cost of containers, insulation, heat exchangers, and other equipment associated with common heat storage materials.
- More effort is required on research and development of low-cost storage systems for specific intermediate- and high-temperature solar applications.
- Heat transfer in solid materials, including direct contact methods, requires considerable re-

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search and innovation if storage in heat-of-fusion materials and gas-solid reactions is to become economically attractive.

be carefully assessed for competing technologies to determine their effects on energy delivery costs.

- For thermal energy storage by reversible chemical reactions, the temperature distribution of the energy delivered from storage, the parasitic power requirements, the energy storage densities, total system requirements, and required shifts in temperature for reaction should
- Specific target applications and their requirements should be identified with major efforts toward developing specific storage technologies to meet these targets over appropriate time spans.

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SERI Report Summary

Comparative Ranking of 1-10 MW_e Solar Thermal Electric Power Systems: An Executive Overview

John P. Thornton
Kenneth C. Brown
Alan L. Edgecombe
Joseph G. Finegold
F. Ann Herlevich
Thomas A. Kriz

Objective: Project the mid-1980 cost and performance of selected generic solar thermal electric power systems in the 1 to 10 MW_e range for utility application.

Discussion: The primary question addressed in this report is: What is the most appropriate long-term ranking of solar thermal technologies for small electric power utility applications in the 1 to 10 MW_e range? The information discussed was compiled as a part of the Small Solar Thermal Electric Power System Study (SPSS).

There are three products resulting from the study: a ranking of generic solar thermal power systems, a uniform methodology for comparing solar power plants of all types and applications, and a flexible computer code that simulates the performance and projects the life-cycle cost for these plants.

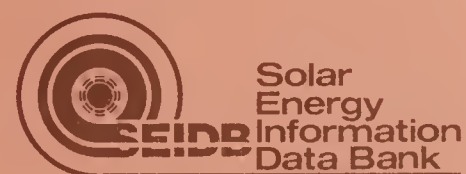
The major product of the study is an ordered ranking of 11 grid-connected generic solar thermal electric power systems evaluated at capacities of 1, 5, and 10 MW_e and capacity factors of 0.7 and 0.4 — corresponding to no storage and lowest busbar cost yields, respectively.

The 1 to 10 MW_e ranking was conducted as part of an overall evaluation of 0.1-10 MW_e solar thermal electric generation systems for both utility and industrial applications.

Conclusions:

- Vigorous subsystems and systems development should be pursued for the point-focus central receiver system with Rankine power conversion and the parabolic dish collector system with distributed Sterling engines.
- Parabolic dish collector technology should be given highest priority in solar component development.
- A limited research and development effort should be directed toward the improvement of subsystems and systems that use parabolic dish collectors with central Rankine power conversion, parabolic dish collectors with distributed Brayton engines, and point-focus central receivers with Brayton power conversion.
- The parabolic trough and low concentration nontracking compound parabolic collector concepts should be actively encouraged for

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development in other applications, and close attention should be paid to developments that would enhance their suitability for small electric power applications.

- Line-focus central receiver, fixed-mirror, distributed focus bowl system, segmented trough with tracking receiver, and shallow solar pond systems should not be included in the small solar electric power systems program.

- Close attention should be paid to the requirements of user markets to define performance, cost, and reliability goals. Goals should be refined on a regular basis.

- A reexamination of generic systems should be made periodically to include new data that results from technology developments.

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Optical Analysis of Point Focus Parabolic Radiation Concentrators

Paul Bendt
Ari Rabl

Objective: Present a simple formalism for analyzing the optical performance of point focus parabolic radiation concentrators.

Discussion: Parabolic reflectors are used to concentrate incoming sunlight onto a smaller receiver. In the analysis presented, in order to account for off-axis aberrations of the parabola, an angular acceptance function is defined as that fraction of a beam of parallel radiation incident on the aperture which would reach the receiver if the optics were perfect. The radiation intercepted by the receiver of

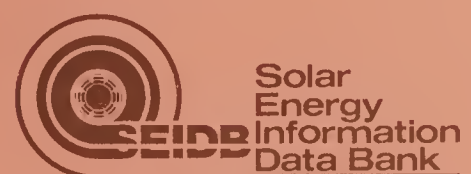
a real concentrator is obtained as a convolution of angular acceptance function, of optical error distribution, and of angular brightness distribution of the radiation source. Losses resulting from absorption in the reflector or reflection at the receiver are represented by a factor which is the product of the reflectance of the reflector and the absorptance of the receiver.

Conclusions: For numerical calculations, this method is far more accurate and timesaving than the ray-tracing method.

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SERI Report Summary

Analysis of the Omnium-G Receiver

Mark Bohn

Objective: Present results of a thermal analysis of the Omnium-G receiver at SERI.

Discussion: The analysis technique used is generally applicable to solar thermal receivers using a directly heated thermal mass. The thermal loss coefficient, including reradiation losses, agrees with the experimentally measured thermal loss coefficient.

The rate of heat transfer to the working fluid is analyzed. The analysis is used to show that the Omnium-G receiver is well matched to the water-steam working fluid because the steam outlet temperature is almost the same as the receiver temperature.

A general procedure for calculating receiver performance is presented. Using this procedure the energy delivery to any working fluid, the delivered temperature of the working fluid, and the pressure

drop through the receiver can be determined. An example of the calculation is presented.

Four appendices give details of the receiver, the methods used in calculations, sample calculations, and results. Three figures and two tables complement the text.

Conclusions:

- The thermal loss coefficient calculated using the method presented agrees well with the experimentally calculated thermal loss coefficient.
- The general procedure presented for calculating receiver performance may be used to determine: energy delivery to working fluid, delivered temperature of the working fluid, and pressure drop through the fluid.

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SERI Report Summary

Heliostat Production Evaluation and Cost Analysis: Executive Summary

J. F. Britt
C. W. Shulte
H. L. Davey

Objective: Provide the factory cost for the production of heliostats, in 1979 dollars.

Discussion: This study estimates heliostat costs by examining the current generation of heliostats from the perspective of contemporary manufacturing technology. Factory cost is defined as the sum of all direct labor, material, and overhead costs that are incurred in the manufacture of a heliostat and its packaging for shipment. Transportation, installation, taxes other than plant real taxes, profit, selling expenses, and all other profit and loss items are excluded from the

analysis. The analysis is performed for two production volumes: 25,000 heliostat units per year and 250,000 heliostat units per year.

Six figures and six tables accompany the text.

Conclusions: The current factory cost for manufacturing heliostats is \$95.99 per square meter for 25,000 units per year and \$67.95 per square meter at 250,000 units per year. For 25,000 units per year, this implies an installed price of \$122.12 per square meter.

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SERI Report Summary

Solar Thermal Repowering Utility Value Analysis: Final Report

Roger Taylor
John Day
Brian Reed
Mike Malone

Objective: Define and quantify the value of repowering to electric utilities.

Discussion: Repowering is the retrofitting of solar central energy conversions systems to existing steam-electric generating stations. To meet the above objective, it is necessary to determine the components of value as a function of solar technology penetration and time. This must be done on a dynamic basis by determining the initial conditions of the utility and then comparing various expansion plans with and without solar penetration.

For assessment purposes, a hypothetical utility system, based upon the Electric Power Research Institute (EPRI) synthetic utility system was chosen as representative of a utility in the southwestern U.S., an area considered prime for repowering.

The following assumptions were made in the analysis:

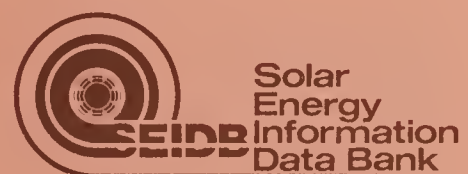
- modified EPRI synthetic utility system,
- moderately high Southwest U.S. insolation,
- oil escalating at 12 percent per year,
- high-performance solar plants,
- only storage-buffered and three-hour storage-coupled thermal plants considered,

- penetration scenarios achieving a maximum of eight percent of system capacity by 2009, and
- no special solar tax credits or other incentives.

Conclusions: Ten key findings were obtained from the analysis:

- Many situations exist where heliostat values are greater than the cost goals that have been proposed.
- The relatively high value of solar energy may not be enough to compete with new base load coal and nuclear generation devices.
- The value of solar thermal electricity is not constant, nor even monotonically increasing with time.
- Solar thermal value trends suggest a program plan emphasizing early solar thermal repowering, followed by later construction of new stand-alone plants.
- The current high value of displacing oil-fired capability is a near-term stimulus for solar thermal repowering.
- Dynamic analysis reveals financial problems not identified by static analysis.

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- Optimizing the conventional generation mix around a solar penetration scenario does not eliminate the market effects of that penetration.
- Dynamic analysis is essential to understanding the value questions for a power plant in a changing environment.
- Institutional constraints on nuclear and coal generation facilities strongly affect the time value of solar thermal capacity.
- Taking capacity credit for solar capability of a system that is adding only new baseload capacity may be economically unwise.

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SERI Report Summary

Evaluation Techniques for Determining the Reflectivity, Specularity, and Figure of Solar Mirrors

J. W. Griffin
M. A. Lind
L. D. Phillipp

Objective: Report on mirror evaluation techniques for the determination of reflectivity, specularity, and figure parameters for heliostat mirror facets and evaluate the feasibility of these techniques to the heliostat mirror quality assurance program.

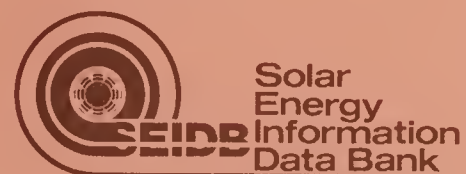
Discussion: This report discusses several optical techniques for determining the above parameters for a heliostat mirror surface. For each technique, the theory and application are covered in detail. The extension of each laboratory technique to field applications is also discussed.

Conclusions: While presently available techniques are useful for laboratory testing of moderately sized optical components, they are not immediately applicable to the problem of quality assessment of large solar optics. It is difficult to alter the techniques to accommodate large optics because of physical limitations or financial constraints. In general, the spatial resolution capabilities of the available techniques are either too stringent (as in interferometry) or too coarse for meaningful results. However, viable assessment techniques should evolve based on the concepts covered in this report.

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SERI Report Summary

Heliostat Production Evaluation and Cost Analysis

J. F. Britt
C. W. Shulte
H. L. Davey

Objective: Define the factory cost of producing heliostats, in 1979 dollars.

Discussion: The study estimated heliostat production costs by examining current heliostats from the perspective of contemporary manufacturing technology. The General Motors Transportation System conducted a production evaluation and manufacturing cost analysis of the McDonnell Douglas Astronautics Company (MDAC) solar central receiver prototype heliostat design. Design and engineering data were collected on the MDAC heliostat design, manufacturing processes were defined, manufacturing labor was developed, and finally a factory cost was established for two volumes of production: 25,000 and 250,000 units per year. For each production level, the analysis was performed for 75 percent and 125 percent of plant capacity. Tucson, Ariz. was selected as the site for the hypothetical plant.

Factory cost is defined as the sum of all direct labor, material, and overhead costs that are incurred in the manufacture of a heliostat and its packaging for shipment. Transportation, installation, taxes other than real plant taxes, profit, selling expenses, and all other profit and loss items were excluded from the analysis.

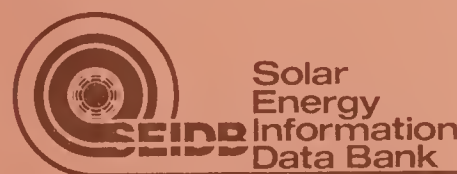
Fifty-two figures and 15 tables accompany the text. Five appendices present detailed data used in analysis.

Conclusions: Current factory cost for manufacturing heliostats is \$95.99 per square meter for 25,000 units per year and \$67.95 per square meter for 250,000 units per year. This implies an installed price of \$122.12 per square meter for 25,000 units per year and \$89.48 for the 250,000 unit rate.

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SERI Report Summary

The Cost of Heliostats in Low Volume Production

K. Drumheller
T. A. Williams
R. A. Dilbeck
G. S. Allison

Objective: Estimate the cost of heliostats in low-volume production.

Discussion: The purpose of investigating low-volume production is to determine the cost of heliostats that can be expected during a demonstration program. This study provides estimated costs for a plant operating continuously for four years at a production rate of 2500 units per year. The approach used is simply to break the cost elements into individual components and then to add them up. The cost elements used include direct materials, direct labor, manufacturing overheads, and plant overhead. The design information used was derived from a prototype design by McDonnell Douglas Corporation. Materials costs

were estimated by requesting engineering estimates or price quotations from suppliers. Labor costs were estimated using industrial engineering analysis. Manufacturing and plant overheads were determined by industry comparison.

Two analyses were made. The first was a scenario where purchased components were primarily used. The other involved the case where most parts were manufactured in-house.

Conclusions: The estimated cost of a heliostat with mostly procured parts is \$10,557. For in-house manufacturing, the cost is estimated to be \$9,153 per unit.

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SERI Report Summary

Heliostat Manufacturing Cost Analysis: Volume I

Kirk Drumheller
Steven C. Schulte
Ron A. Dilbeck
Lloyd W. Long

Objective: Estimate the manufactured cost of the current generation of heliostat designs at various production volumes.

Discussion: This study produced cost estimates for production of a McDonnell Douglas Astronautics Company (MDAC) prototype heliostat design by using estimates of the costs of materials, labor, overhead, and the facilities for two production scenarios. The first scenario was a low-volume facility (25,000 heliostats per year) with some expansion capability, while the second involved a high-volume facility (250,000 heliostats per year).

The study used two independent cost estimating approaches. The first was to obtain vendor quotes on purchased parts and supplies and then to manually compute the cost of the labor and capital required to produce a finished heliostat. The second approach used the SAMICS (Solar Array Manufacturing Industry Costing Standards) model to perform rapid parametric analysis and

economic sensitivity studies. The SAMICS model computes a typical price for a product using a standard procedure for calculating direct and indirect costs. The procedure is implemented by using the SAMIS III (Solar Array Manufacturing Industry Simulation) computer program.

The text is complemented by 22 figures and 23 tables.

Conclusions: The estimates obtained by the SAMICS model and the manual calculations agree closely. The current generation of heliostats should cost approximately \$100 per square meter at 25,000 units per year. The price falls to approximately \$80 per square meter for 250,000 units per year. Additionally, the cost reduction begins at relatively low production levels so that many production savings can be obtained at rates of 5,000 to 15,000 units per year. The SAMICS model and the SAMIS III program are useful tools in heliostat costing studies.

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SERI Report Summary

Solar Thermal Repowering Systems Integration: Final Report

L. J. Dubberly
J. E. Gormely
A. W. McKenzie

Objective: Identify the cost of integrating a solar thermal system into an existing power plant.

Discussion: In considering solar thermal repowering, it has traditionally been assumed that the electrical generating plant was virtually free. This study tests that hypothesis by outlining the sources of repowering integration cost and estimating the magnitude and variability of those costs.

Detailed cost evaluations were performed for six plant configurations:

- 50 megawatt (MW) non-reheat, 50 percent repowering, water/steam receiver;
- 100 MW non-reheat, 50 percent repowering, water/steam receiver;
- 100 MW reheat, 50 percent repowering, salt or sodium-cooled receiver;
- 100 MW reheat, 100 percent repowering, salt or sodium-cooled receiver;

- 350 MW reheat, 50 percent repowering, salt or sodium-cooled receiver; and
- 350 MW reheat, 100 percent repowering, salt or sodium-cooled receiver.

The cost estimates were based on previous power plant cost experience for similar size units, using labor rates representative of the southwestern United States.

Conclusions: Integration cost can be quite low if the plant is in good condition and the major plant systems do not require extensive modification. However, if the turbine, generator, or major auxiliary systems need significant repair, the integration cost increases substantially. The primary conclusion is that it is not possible to generalize in advance what the integration cost will be for a particular plant. Each plant must be carefully evaluated to determine if its age and condition are consistent with cost-effective use as a repowered plant.

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SERI Report Summary

Issued June 1981

Final Report: Comparative Ranking of 0.1-10 MWe Solar Thermal Electric Power Systems

John P. Thornton
Kenneth C. Brown
Joseph G. Finegold
James B. Gresham
F. Ann Herlevich
John S. Kowalik
Thomas A. Kriz

Objective: Present the results of the Small Solar Thermal Electric Power Systems Study (SPSS), a comparative analysis of the major generic solar thermal electric systems.

Discussion: The objective of SPSS was to project the mid-1990 cost and performance of selected generic solar thermal electric power systems for industrial and small utility applications, and to rank them according to potential for future commercial acceptance. Plants were considered with rated capacities of 0.1 to 10 megawatts capacity. Volume I summarizes the results, and Volume II contains tables of data on system performance and ranking methodology data as well as a set of key references.

Volume I contains 55 figures, 80 tables, and 8 appendices which present detailed background information on the procedures, codes, and philosophy of the study, as well as lists of the key people and organizations involved. Volume II presents two figures and 116 tables.

Conclusions:

- Vigorous development of central receiver/Rankine and parabolic dish/Stirling

systems should be encouraged because of their high potential for mid-1990 commercialization.

- High priority should be given to the development of parabolic dish collectors and advanced electric storage technologies because these subsystems are critical to the successful commercialization of many distributed generation concepts.
- A limited research and development effort should be directed toward the improvement of subsystems for the parabolic dish with distributed (focal-mounted) Rankine and Brayton-cycle conversion, the parabolic dish with central Rankine conversion and the central receiver with Brayton-cycle conversion.
- Because of their availability for near-term applications, development of tracking troughs and central receivers/Rankine systems should receive high priority.
- Development of the low concentration non-tracking (CPC) concept should continue. If this nontracking system reaches the performance and cost targets used in this study, it may show

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increased potential because of user preference for low-maintenance systems.

- The line focus central receiver, fixed mirror distributed focus, trough with tracking receiver, and shallow solar pond systems should not be included in the small solar electric power systems program.
- Further analysis of the central receiver/Stirling system should be pursued to determine the practicality of development beyond the conceptual stage.

- Close attention must be paid to the requirements and preferences of potential users. User attitudes may change as the cost of conventional systems and fuels increase; hence, these attitudes should be periodically checked and any changes reflected in the development of small solar thermal systems.

- Demonstration will be required of all concepts to convince potential users that small solar thermal systems can meet their needs. Utilities strongly prefer solar thermal systems that most resemble current conventional systems.

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Objective: Present the results of laboratory measurements made to determine the magnitude of the thermal-loss characteristic of several line-focus receiver designs as functions of the absorbing surface temperature, and to determine which configurations are most effective in reducing receiver heat losses.

Discussion: In the past, testing of line-focus receivers has usually employed outdoor fluid loops. This procedure, however, is both expensive and cumbersome when only the receiver heat loss as a function of temperature is needed, and not the overall collector module efficiency. For this experiment, a simpler method for determining receiver heat loss was developed; briefly, the method involves heating the receiver from the inside using an electric resistance heater. This method offers several advantages over the use of fluid loops. With an electric heater, testing can be performed indoors and does not depend on the availability of solar radiation. Also, a heat transfer fluid and all the associated plumbing, pumps, and fluid heaters will not be required. Data scatter due to uncontrolled variations in wind speed is eliminated (natural convection, of course, still occurs). Only the actual receiver need be available for testing — the concentrating reflector is not necessary; in fact the receiver heat loss test data could be used to help design a suitable concentrator and then to predict the average daily and annual collector efficiencies. Finally, the electric heater method produces data faster than the outdoor fluid loop method; thus, receiver losses can be determined at a minimal cost. Such testing can reveal faulty designs, and it is especially valuable when a receiver configuration is being "fine-tuned" and analysis can-

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Line-Focus Receiver Heat Losses

Douglas A. Dougherty

not be relied upon to quantify performance improvements accurately.

As a part of the indoor testing, the receivers were tested with identical, separately purchased black chrome coated fluid tubes so that differences due to the type of selective coating were removed from the experimental investigation. This effectively focuses attention on the relative merits of the various receiver components exterior to the fluid tube itself. Four generic line-focus receiver designs were investigated in this experiment: fluid tubes enclosed in (1) a glass cylinder, (2) an evacuated glass jacket, (3) a tube with a back reflector, and (4) a tube with back insulation. Heat loss data were also obtained for a bare black-chrome tube for comparison purposes. Results from the laboratory measurements are compared with analytical predictions when appropriate and are presented as graphs of heat lost (in watts per meter of receiver length) versus the temperature of the primary receiving surface. Heat loss data were measured for receiving surface temperatures up to 220°C above ambient temperature.

The 36-page text includes 11 figures and an appendix on sources of error.

Conclusions: This information is especially valuable to receiver designers because, though receivers generally make up only a small percentage cost of a line-focus collector system, they can severely limit the performance of concentrating solar collectors if they are inefficiently designed. By incorporating the most cost-effective design techniques into their receivers, designers can make both collectors and total systems more efficient and more competitive with other designs.

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Solar Report Summary

Issued November 1982

Near-Term Improvements in Parabolic Troughs: An Economic and Performance Assessment

R. Gee
L. M. Murphy

Objective: Quantify the performance potential and economic merit of selected parabolic trough component improvements from a systems viewpoint.

Discussion: The component improvements considered are evacuated receivers, silvered-glass reflectors, improved receiver selective coatings, optically more accurate concentrators, and higher transmittance receiver glazings. First, the systems benefits due to the proposed components are quantified for a realistic range of operating conditions and for typical annual operating cycles. Second, an upper-bound cost increase is computed for each improvement. Finally, the increase in rate of return for a parabolic trough system is analyzed for the improvement. The study emphasizes the system and annual operating benefits of the specific component improvements,

but does not focus on the details of component improvement.

Fifteen figures and six tables are included. Line-focus receiver heat loss coefficients are treated in the appendix.

Conclusions: Evacuated receivers and silvered-glass reflectors have the greatest potential for improving system performance. Either improvement can increase system performance by twenty percent of 150°C (302°F) operating temperatures, and more at higher temperatures. The evacuated receiver has the most cost leverage of the components considered, due to its potential for improved performance and because line-focus receiver costs are small relative to total system costs.

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Issued November 1982

An Organic Rankine Cycle Coupled to a Solar Pond by Direct-Contact Heat Exchange — Selection of a Working Fluid

John D. Wright

Objective: Choose the optimum working fluid for use in an organic Rankine cycle coupled to a solar pond by a direct-contact boiler and to show the methodology developed.

Discussion: This report presents the methodology employed to choose the working fluid for this application and illustrates the type of savings which can be attributed to direct-contact heat exchange. Potential saturated and halogenated hydrocarbon working fluids are evaluated for low solubility in the pond to minimize

fluid losses, net conversion-cycle efficiency, and sufficient energy density at operating conditions to result in a turbine of reasonable size and cost. A rough breakdown of plant cost is presented to illustrate the saving available with direct-contact boilers in place of conventional shell-and-tube boilers.

Conclusions: Pentane is identified as the ideal working fluid for this application, because it shows the highest net cycle efficiency, low solubility, and reasonable turbine cost.

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Solar Report Summary

Issued November 1982

Structural Design Consideration for a Line-Focus Reflective Module using Inexpensive Composite Materials

L. M. Murphy

Objective: Describe and analyze a potentially low-cost design approach for line-focus solar concentrating collectors.

Discussion: In the development of parabolic troughs, structural design philosophies have focused on meeting a given performance standard and withstanding expected wind and weight loading with a high degree of certainty. Having established some basic, sound, workable structural approaches, researchers have dedicated much of their recent efforts to reducing delivered energy costs by improving optical and thermal performance and manufacturability. The main structural concern with troughs has been the survival of the trough and its subcomponents in extreme wind environments. These wind survival requirements and the desire to be able to utilize any reflective surface, including glass, have led to the development of reflective modules that are fairly stiff to bending. When glass is used for its desirable optical properties, the corresponding material/structural response (of the glass) is often the controlling structural design factor. The current stiffness requirement not only allows protection of a glass reflector in survival conditions but typically permits designers to ignore losses in performance that result from wind-induced deformations under normal operating conditions.

Another common system and structural design approach is to rotate (track) the reflective modules along a row of collectors. From a structural perspec-

tive, this approach requires significant torsional rigidity if more than one collector is driven in series (typically, three or four collectors on each side of a drive mechanism are driven in series). The most common approach to meeting this design requirement is to use a torque tube for torsional rigidity with reflective modules mounted with the convex face against the tube. Torque tubes represent one of the simplest and most efficient ways of transmitting torsion loads along an axis, especially as opposed to using large, open, parabolic sections. Two common rotation approaches have been used to minimize cost and required tracking loads. The first is to rotate the trough about the center of the torque tube. A second approach is to offset the rotation center from the torque tube center to the mass center by adding structural arms. One major complication induced by both of these approaches, however, is that the receiver tube must articulate with the structure, since it is fixed relative to the module (remaining in the focal line of the trough). This, in turn, necessitates flexible interconnections.

This report presents results of the structural and design analysis of one design concept of a potentially low-cost (albeit probably lower-performance) trough concept. The present approach deviates significantly from several current, widely accepted design philosophies. Specifically, the current prototype uses a reflective module with low flexural rigidity and is to be implemented in a system in which collectors will be driven from row to row, rather than along the row. The

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reflective module will be rotated about the receiver tube. We do not claim here that the concepts analyzed and proposed are either optimum or generalizable. Rather, we prefer to lend some insight into some of the structural and mechanical design problems associated with departing from traditional trough structural design, propose some possible resolutions of those problems, and describe some potential benefits that could accrue from such departures.

This 60-page report addresses the progress to date on the study of structural design aspects of novel reflective modules and their respective support systems. The text is supplemented by 26 illustrations and 6 tables. The adequacy of the rim drive subsystem will be the subject of a future report, as well as the fabrication, installation, and testing of the prototype experiment. The present work should provide insight into

the structural adequacy of flexible modules for potentially low-cost concentrating reflector designs. It also demonstrates a feasible, potentially attractive method of supporting these modules.

Conclusions: It is anticipated that this approach may lead to larger trough deformations under wind and weight loading which will result in somewhat lower system thermal performance than will occur with more traditional designs. However, it is also anticipated that cost reductions (which, from preliminary costing studies appear to be potentially quite dramatic) will more than offset the negative effect of performance reduction and, therefore, result in a reduced cost of delivered energy and lower initial solar-system capital investments. The analysis indicates so far that some of the approaches suggested here could have significant merit.

Solar Report Summary

Issued November 1982

Scatterplate Flux Mapping for Solar Concentrators

Keith Masterson
Mark Bohn

Objective: The work reported here concerns the development of a technique for mapping the spatial distribution of high-power radiant flux present at the focus of point-focus solar concentrators.

Discussion: The system performance of point-focus concentrating solar collectors depends partially on the optical accuracy of the concentrating subsystem. In general, the smaller the focal area, the more efficient the power conversion. An ability to map the flux levels is necessary for a meaningful evaluation of the concentrator. A high-resolution, high-speed mapping technique was necessary for SERI to test one particular concentrator. An optical technique using a video camera and digital-frame store unit to record the spatial radiance of the sunlight reflected off a scatterplate at the concentrator's focus was developed for this task. The solar reflectance and lightscattering properties of several potential scatterplate materials were measured to see how closely they match the ideal Lambertian characteristics desired for this application. An error analysis was carried out to determine the expected errors in the flux distribution due to the measured deviation from the ideal Lambertian light-scattering characteristics.

Conclusions: The scatterplate flux mapper that resulted from this effort also has applications to other types of concentrators.

- A working scatterplate flux mapper that has the desired resolution and speed was constructed and used to determine the flux distribution of a test concentrator.
- The basic system is quite versatile and has application in other areas, such as for line-focus concentrators, daylighting measurements, and cloud-cover monitoring.
- The scatterplate chosen was a porous ceramic (alumina) that has very high resistance to fracture from thermal shock and almost ideal light-scattering properties.
- The errors due to the nonideal light-scattering properties of the various scatterplates tested were less than the resolution in intensity (0.4%) by the signalprocessing electronics.
- In choosing a video camera for flux-mapping applications, it is important to avoid systems with automatic gain and limit circuits that produce good TV pictures but severely reduce the usable dynamic range and linearity from the image tube itself.
- A metallic, water-cooled plate having a matte white or gray painted surface with nearly Lambertian light-scattering characteristics is recommended for future applications to map high flux levels.

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Solar Report Summary

Issued September 1983

Second Generation Heliostat Evaluation

Summary Report

Heliostat Development Division
Sandia National Laboratories
Livermore

Objective: Evaluate the five heliostat designs produced in the Second Generation Heliostat Development Program.

Discussion: Five contractors were funded to develop second generation heliostats: ARCO Power Systems, Boeing Engineering and Construction, Martin Marietta Corporation, McDonnell Douglas Astronautics Company, and Westinghouse Electric Corporation. This development supports the Department of Energy (DOE) Solar Central Receiver Development Program. Each contractor's effort was evaluated by a Sandia evaluation panel which was assisted by a panel of potential users and a review committee.

The evaluation of each design provides the following information:

- design summary
- mass-production and installation highlights
- testing results
- design strengths, concerns, and potential solutions

- user concerns
- comparisons with requirements
- readiness for near-term application
- further research and development requirements
- published reports of testing and analysis
- public presentation of evaluation results.

Each contractor completed a detailed mass-production design for its heliostat, prepared a conceptual design for production of 50,000 heliostats per year, and estimated the price of installed heliostats in a fifty megawatt electrical power plant. With the exception of Westinghouse, two prototype heliostats were built and tested by each contractor and also tested side by side at the Central Receiver Test Facility in Albuquerque, N.M.

Conclusions: With low risk design changes, the four tested second generation heliostats are viable designs. The Westinghouse heliostat evaluation could not be completed because prototype hardware was not produced. Detailed cost estimates indicate that the DOE heliostat cost goal can be met at low production rates.

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Solar Report Summary

Issued September 1983

Sizing of Direct-Contact Preheater/Boilers for Solar Pond Power Plants

John D. Wright

Objective: Review the methods available for sizing a direct-contact preheater/boiler for an organic Rankine cycle coupled to a solar pond; develop conceptual designs for the heat exchanger; and determine what areas require further research.

Discussion: Following a brief introduction, the overall operation of the solar pond, the power cycle, and the heat exchanger is discussed. Methods are discussed for determining the cross-sectional areas of the liquid/liquid and vaporization zones, and heat transfer is treated for each zone. Complete heat exchanger designs are discussed, and research required for confident sizing of such devices is described.

Fourteen figures and two tables are included. Eight appendices cover the details of the mathematical techniques used in sizing and performance prediction.

Conclusions: Methods exist for predicting the cross-sectional area and height of the liquid/liquid section, but agreement among the various methods is poor. Methods for predicting flooding and holdup have been validated only in small laboratory-scale apparatus. Existing correlations are inadequate for use in the design of the boiling section of the plant. Research is required on vaporization, heat transfer, flooding behavior in spray columns, and on flow characteristics in the three-phase region.

Preliminary design and cost figures derived for a fifty megawatt (thermal) plant indicate that in all cases the direct-contact heat exchanger costs much less than an equivalent shell-and-tube boiler. However, research is required to ensure that an installed direct-contact preheater/boiler will work as intended and to determine the effect of off-design conditions.

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Issued January 1985

A Beer's-Law-Based, Simple Spectral Model for Direct Normal and Diffuse Horizontal Irradiance

Richard E. Bird
Solar Energy Research Institute

Objective: To formulate a simple spectral model for calculating solar irradiance that can be used on small computers and provide accurate results.

Discussion: In the past, accurate calculations of terrestrial spectral irradiance, especially the diffuse component, have necessitated the use of complex radiative transfer codes on a large main-frame computer. Such codes could thus be used by only a small group of researchers. In the work reported here, we have attempted to formulate a reasonably accurate, simple spectral model that can be applied to a broad range of atmospheric conditions.

Thirteen figures and seven tables are included.

Conclusions: A simple spectral model was formulated that produces a spectrum between 0.3 and 0.4 μm wavelength of approximately 10 nm spectral resolutions. The diffuse component of the radiation obtained from this model is limited to that falling on a horizontal surface. The only inputs required for the model are turbidity coefficients, amount of water vapor, amount of ozone, solar zenith angle, surface pressure, and ground albedo.

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Solar Report Summary

Issued January 1985

Catalog of Automatic Sun-Following Trackers

Thomas L. Stoffel
Solar Energy Research Institute

Objective: To present a catalog of automatic sun-following trackers that can be used for pyrheliometric measurements of the direct normal (beam) component of solar radiation. The availability of improved trackers will allow an increase in the number of monitoring stations that measure solar radiation resources and will improve the quality of these data.

Discussion: The need for a catalog of automatic sun-following trackers to make pyrheliometric measurements was identified by the members of the International Energy Agency's (IEA) Solar Heating and Cooling Program attending the Task V meeting (Use of Existing Meteorological Information for Solar Energy Applications) held on October 23-24, 1980, in Downsview, Ontario, Canada. Several tracking devices that could satisfy the generally recognized need for continuously monitoring direct normal solar radiation were then in various stages of development and testing. A questionnaire was distributed to collect the information presented in this report. The responses are included as appendices to this report.

Historically, limited amounts of direct normal solar radiation data have been available to assess the potential of this solar radiation component as a possible form of renewable energy. Recent advances in microelectronics have improved design opportunities for more accurate and dependable measurements from pyrheliometers mounted in sun-following trackers. The need for improved monitoring of the solar radiation resource is reflected by the diversity of available tracker designs.

Forty-eight figures and two tables are included.

Conclusion: The instruments and concepts presented here are results of the need for instrument platforms (trackers) on which to mount pyrheliometers (radiometers) for continuous measurements under widely varying weather conditions. The measurements of direct normal solar radiation made possible by a network of these monitoring devices would become an important part of a radiation resource data base useful for research in various solar energy conversion technologies, climate studies, and other meteorological applications.

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Solar Report Summary

Issued June 1986

Objective: Present the results of an assessment of concentrator research and development and provide recommendations for future concentrator research and development (R&D).

Discussion: Concentrator R&D has always been an integral part of the solar thermal technology program. A considerable amount of R&D has been successfully concluded within the central and distributed receiver programs: over 25 line-focus (primarily parabolic trough) designs, 13 heliostat designs, and 8 parabolic-dish designs have been created and tested under the sponsorship of the Department of Energy (DOE). Mass-production costs have been estimated for several of these designs, and materials and components research is under way to identify areas for both cost and performance improvements.

The assessments and recommendations in this report were performed based on the following approach:

- Determine the development status of each concentrator technology
- Assess the capability of each technology to achieve close- and long-term targets when mass produced
- Identify technology options or development approaches that offer a good potential for meeting these targets
- Identify additional study areas that could lead to further concentrator R&D needs.

Assessment of Solar Thermal Concentrator Research and Development

L. G. Radosevich

R. S. Caputo

This publication presents a history of technology development for the major concentrator types (heliostat, parabolic dish, and line focus), followed by a description of manufacturing activity and cost-estimate history for each concentrator type. An assessment of these activities and ongoing activities is included, as are recommendations for future concentrator R&D.

Six figures and eight tables accompany the report.

Conclusions: Future concentrator R&D should address the following issues:

- How can the Solar Thermal Technology Program achieve a level of dish-concentrator development comparable to the heliostat and line-focus concentrator developments in a cost-effective way?
- What concentrator activities offer the best prospects for meeting the long-term cost goals of the Solar Thermal Technology Program?
- What are the heliostat performance requirements for high-temperature system applications, and can existing designs satisfy these requirements?
- How close is each solar thermal technology to bridging the transition from R&D to applications, and how close is each technology to meeting the long-term goals of the Solar Thermal Technology Program?

Additionally, specific recommendations are included for each of these issues.

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Solar Report Summary

Issued June 1986

Objective: Present a method for estimating the total convective energy loss from a receiver of a solar central receiver power plant.

Discussion: In central receiver systems for large-scale electric power generation or process heat production, an array of heliostats focuses sunlight onto a receiver positioned on a tower. The solar energy absorbed by the receiver heats a working fluid that is used in a thermal power-plant cycle. The receiver, which operates at a high temperature, loses some of the absorbed energy by convection and radiation to the environment. This loss of energy from a receiver is important, since efficient absorption and transfer of solar energy to the working fluid by the receiver is critical to the central receiver concept. Receiver efficiency significantly affects plant performance, plant capital cost, and the cost of the energy produced.

In outlining a method to estimate the portion of the energy that a receiver loses to the environment by convection heat transfer, two types of receivers are considered in detail: a cylindrical, external-type receiver and a cavity-type receiver. A typical external receiver is a cylinder or a flat plate, and a typical cavity receiver is a multisided enclosure with one open side, which serves as an aperture through which solar energy is focused. The method presented is intended to provide a designer with a tool for estimating the total convective energy loss. This tool is based on current knowledge of convective heat transfer from receivers to the environment and is adaptable to new information as it becomes available. The report also

Estimating Convective Energy Losses from Solar Central Receivers

D. L. Siebers

J. S. Kraabel

describes a method for estimating the uncertainty in the convective energy loss estimate.

The method itself is described in four sections: the first concerns the parts of the method that are common to any receiver design; the second discusses those parts that are specific to a cylindrical, external-type design; the third presents those parts that are specific to a cavity-type receiver; and the fourth presents the method for estimating uncertainty.

Eleven figures accompany the text, as well as three appendices that cover the following areas: convective energy losses from the cylindrical, external receiver of the 10 MW_e Solar Thermal Central Receiver Plant in Barstow, Calif.; convective energy losses from the cavity receiver of the International Energy Agency Small Solar Power Systems Project in Almeria, Spain; and a review of the literature related to the estimation and correlation of mixed convection heat transfer.

Conclusions: This report provides forced convection correlations for external cylindrical receivers and natural convection correlations for both cavity and external receivers.

The report recommends further use of the models for convective heat loss and comparison of the model predictions with actual measurements. The authors suggest conducting heat transfer experiments for external receivers and wind velocity and turbulence levels on cavity receivers.

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Solar Report Summary

Issued June 1986

Objective: Present the results of work performed at the University of Utah to construct a direct-contact tower heat exchange apparatus and evaluate the heat transfer between hot water and pentane in the parameter range applicable to power production from a salt-gradient solar pond.

Discussion: Because of the inherently low efficiency of low-temperature power cycles driven by salt-gradient solar ponds, the amount of heat that must be transferred is large relative to the electrical output. For solar ponds the ratio is approximately 10 to 1, compared with 3 to 1 for plants using nuclear or fossil fuels. Using a direct-contact preheater/boiler in place of a conventional shell-and-tube unit may reduce the plant cost by about 25%.

The experimental design of a 0.62-m (24-in.)-diameter direct-contact tower heat exchanger is presented, and the procedures followed during the research are also described. In the present application, commercial-grade pentane is boiled while in direct contact with hot water, with the water flowing downward and the pentane flowing upward. Determination of the flooding limit of the tower is emphasized. A water-inlet temperature of 85°C (185°F) was used; the pentane-inlet temperature of approximately 30°C (86°F) varies somewhat with ambient temperature. Several values of tower operating pressure in the range of 1.2-3.2 atm are evaluated. Water and pentane flow rates are varied

Laboratory Measurements of a Direct-Contact Heat Exchanger

R. F. Boehm

to determine their effects on flooding. The direct-contact tower and a simple spray-tower configuration are compared; correlations of the flooding limits are included.

Nineteen figures accompany the text, as well as one appendix that details data analysis techniques. An explanation of nomenclature is included.

Conclusions: The following conclusions are presented:

- The controlled variable that most affects the temperature profiles within the column is the vessel pressure.
- In general the baffled tower operated very similarly to the simple spray tower, although the latter demonstrated slightly higher heat-transfer performance and a slightly higher flooding level.
- Variation of the volumetric heat-transfer coefficient was greatest when plotted against the pentane mass flow rate.
- Pressure at the flooding point varies with the inverse of the pentane flow rate, at constant brine flow and inlet temperature. The pentane-inlet temperature, however, could not be controlled closely in this research, and this variable introduces uncertainty in these results.

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Issued June 1986

Objective: Present a summary of observations made by the Laboratory of Biomedical and Environmental Sciences (LBES) assessing the ecological consequences of constructing, testing, and operating the 10 MW_e solar thermal power system near Barstow, Calif.

Discussion: The Department of Energy (DOE), the Southern California Edison Company, the California State Energy Commission, and the Los Angeles Department of Water and Power constructed a 10 MW_e solar thermal power system. This project, Solar One, is the first large central receiver-type solar facility for generating electricity in the country and the largest such installation in the world.

This report presents research conducted at Solar One on the possible ecological effects of the plant. Following the introduction and a description of the general site before, during, and after construction, a section presents the environmental monitoring plan and details abiotic and biological monitoring, as well as monitoring during the testing and operation of Solar One. The fourth section consists of the abiotic measurements taken at Solar One: rainfall, soil temperatures and moistures, micrometeorology, air quality, and surface-soil movement. The fifth section presents observations of vegetation before, during,

Ecological Observations at the Site of the 10 MW_e Solar Thermal Power System (1978-1984)

Editors

Robert G. Lindberg

Frederick B. Turner

and after construction of the facility. Another section describes animal studies, particularly those done on arthropods, reptiles, rodents, birds, and other sensitive species.

The report is well documented with 21 figures and 25 tables.

Conclusions:

- The effects of the construction of Solar One on the surrounding ecosystem are that the wind has removed loose sand from the cleared heliostat field, which will indirectly affect some species of plants and animals in nearby areas.
- The central receiver and tower, the reflective surfaces of heliostats, and the standby points near the receiver surface at which heliostats were brought to focus are potential hazards to indigenous wildlife. The hazards involve collision with structures and incineration in the heliostat beams.
- The presence of Solar One affected certain micrometeorological states in downwind areas. Also, air-temperature profiles among an array of heliostats differ from inside concurrent measurements.

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Solar Report Summary

Issued December 1986

Molten Salt Receiver Subsystem Research Experiment — Executive Summary Phase I, Final Report

Babcock & Wilcox Co.

Objective: Present the preliminary design of a molten salt receiver subsystem for application to solar thermal central receiver power plants.

Discussion: This summary presents the results of the program conducted by the Babcock & Wilcox Company to develop a design for a molten nitrate salt receiver subsystem for use in a solar thermal central receiver power plant. First, the report describes the conceptual design evaluations that were made during the proposal phase to establish the base design. Then the design requirements are presented, establishing the functional requirements for the receiver subsystem, the design condition, and the environmental requirements. A detailed description of the subsystem components is also given. Following this, the development requirements are outlined with a discussion of the need for a subsystem research experiment and appropriate laboratory tests. A 10-ft long tube panel

was manufactured to prove the acceptability of the fabrication procedures, and the results of this effort are included. In addition, the cost and schedule are presented.

Nine tables and thirteen figures accompany the text.

Conclusions: The preliminary design effort established that current technology will successfully support the design, fabrication, and operation of large-scale solar thermal receivers. The report also recommends that research and development be continued emphasizing subscale component tests with the aim of (1) testing critical components and demonstrating technical feasibility to potential users, and (2) refining designs to lower capital and maintenance costs.

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Solar Report Summary

Issued April 1989

Objective: Determine the feasibility and potential cost-effectiveness of stressed membrane heliostats for use in solar central receiver systems that are designed for electric power and process heat applications.

Discussion: This report describes research performed at Science Applications International Corporation (SAIC) in San Diego, California under subcontract to Sandia National Laboratories in Livermore, California. A commercial, mass-producible, 150-m² stressed membrane heliostat was designed and its manufacturing, operation, and installation costs were assessed. A 50-m² prototype heliostat was fabricated and evaluated to determine the optical quality and viability of the commercial heliostat design.

The stressed membrane heliostat design described in this report utilizes a thin stainless steel double membrane that can be safely stretched without tearing to produce a smooth surface. Conventional fabrication techniques at high production rates have been used to produce glass-smooth large area membranes, with membrane seams welded at the rate of 60 inches per minute. The design is light (10.7 kg/m² or 2.2 lb/ft²), strong, durable, stiff, and optically smooth. A pressurized bladder stressing system allows the membrane to be stressed uniformly after being attached to the ring. Some problems with optical figure, image shape, and beam profile can be

Development of Stressed Membrane Heliostat Mirror Module Final Report

B. L. Butler
K. Beninga
W. C. Loomis
P. J. Royval

corrected, but were not demonstrated on the prototype. The focus control system is operational and is capable of providing electronically controlled focal lengths from infinity to 600 feet.

The first 150-m² stressed membrane heliostat has an installed cost of \$89.80/m², utilizing current material prices for the reflector. With an advanced low-cost silvered polymer mirror, the heliostat installed costs would be \$64.57/m². Learning curves and experience could lower these costs further.

Figures and tables accompany the text; two appendices are also included.

Conclusions: The lessons learned from the 50-m² prototype heliostat are:

- The stainless steel membrane will yield optically smooth surfaces in very large areas.
- Yielding of the thin stainless steel membrane, while it was stretched, increased its smoothness and reduced ring out-of-plane distortions.
- Seaming of the membranes is critical for uniform stress distribution and to minimize out-of-plane forces.
- The effective ring out-of-plane stiffness must be increased in the design.
- Effects of manufacturing tolerances on membrane optical smoothness and ring shape need to be defined experimentally and analytically.

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Solar Report Summary

Issued April 1989

Objective: Evaluate the feasibility of using the stressed membrane reflective assembly for heliostat design and fabrication.

Discussion: This report describes research performed by Solar Kinetics, Inc. of Dallas, Texas under subcontract to Sandia National Laboratories in Livermore, California. The stressed membrane reflector assembly is a unique concept designed to reduce the cost of a heliostat. The system reduces cost by resisting and distributing loads. The authors of this report have introduced a number of features into the stressed membrane reflector assembly design that differ from earlier conventional designs. One major departure is that the stressed membrane carries loads through tension rather than through bending.

The stressed membrane module presents an optical quality surface in response to a variable load environment. The module provides an efficient structure for load transfer and responds actively to load changes. Focusing is regulated by altering the pressure differential across the front surface of the assembly with a simple axial fan with speed control. The stressed membrane assembly makes efficient use of material and is easily fabricated by a continuous coil line process.

The chosen design is a monolithic mirror module with 150 m² of aperture. Mirror module weight is approximately 3kg/m² (6.7 lb/m², 0.6 lb/ft²), the total reflector assembly weight is 9.3 kg/m² (20.4 lb/m²,

Development of the Stressed Membrane Heliostat

Solar Kinetics, Inc.

1.9 lb/ft²). The ring and membrane are fabricated from aluminum, a silvered polymer provides the reflective surface, and the support structure is steel. The design is largely stress critical; that is, material requirements are determined based upon stress in high winds and not by deflection or optical quality.

The report is developed in three sections. The first describes the methodology and conclusions reached in analyzing the stressed membrane reflector assembly. The second summarizes the fabrication process, facility requirements, and cost breakdowns. The third describes the testing and construction experience gained by the authors in fabricating the prototype reflector assembly. The report contains 63 figures and 22 tables.

Conclusions: The stressed membrane reflector assembly is a suitable structure for reducing heliostat costs. Savings are realized not only in the reflector assembly itself, but also in the associated pedestal/drive assemblies, which can be reduced in size. The report estimates first-year costs per square meter of a stressed membrane reflector assembly to be \$28.30. Associated structures would cost another \$26.96, for a total of \$55.26 per square meter. This compares with \$71.19 for a second-generation glass-metal design optimized and increased to an identical aperture (all costs in 1985 dollars). The stressed membrane assembly would be less expensive than glass-metal designs to fabricate, even in moderate volume.

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Solar Report Summary

Issued April 1989

Objectives: Define the structural and optical membrane response issues associated with uniform pressure loading of initially flat membrane surfaces into nearly parabolic surfaces. Large deformations and the resulting reflector shapes that are needed for parabolic dish concentrator applications and that are accompanied by inelastic material response are of particular interest. Further, the report identifies the various structural/material phenomena that make the resulting surface contours nonparabolic and to quantify the impact of these effects as much as possible.

Discussion: Stretched membranes for concentrating solar collectors offer the prospect of being very lightweight, structurally efficient, potentially low cost, and potentially similar in optical performance compared to the more conventional rigid glass/metal concentrator design approaches used in current heliostat and parabolic dish applications. This work, concentrates on the membrane contour or shape, which is of primary importance to the optical performance of the concentrator. In particular, it investigates the structural and optical membrane response issues and the class of membrane shapes that result from the membrane-formation process. In addition, it examines the deviations from the desired parabola resulting from uniform pressure loading of circular, axisymmetric, and initially flat membrane surfaces having uniform thickness. Such a pressure-loading, shape-forming procedure has been used to develop prototypes of stretched-membrane reflector modules for both parabolic dish and heliostat applications. The parabola is the basis of comparison since it is the most desired contour for both focusing heliostats and parabolic dishes, and the degree to which the parabola is approximated will determine the collector performance. Also discussed are the limitations and the optical-quality implications of using this approach to form the membrane reflector surface. Though the results of this study are applicable to both membrane heliostats and dishes, the major emphasis of this work is on dish applications.

The Formation of Optical Membrane Reflector Surfaces Using Uniform Pressure Loading

L. M. Murphy
C. Tuan

Unfortunately, as described in more detail later, homogeneous and axisymmetric membranes that are uniformly pressure loaded will in general assume a surface shape that is not parabolic. In fact, for most cases, the limiting shape will be spherical rather than parabolic. This is because, as can be shown for a uniformly pressure-loaded membrane, with constant thickness and with uniform tension in the membrane (both spatially and in direction), the resulting membrane surface is spherical based on equilibrium considerations alone. This is true whether the membrane material response is elastic or inelastic. Note, however, that in some situations, the sphere can provide a quite adequate approximation to the parabola.

The following three primary issues are addressed in this report to assess the adequacy of pressure-forming optical reflector surfaces: (1) the adequacy with which a spherical surface can approximate the ideal parabola, (2) shape distortion relative to parabolic and spherical contours caused by elastic material response, and (3) membrane surface shapes resulting from inelastic material response. A quantified description of the structural/surface contour response of the optical membrane surface is provided to aid in the design of stretched membrane concentrators. Since the emphasis of this investigation is on dish applications, the most extensive descriptions and discussions are presented for the large deformation analyses in which inelastic material response is dominant.

This report contains 28 figures, two tables, and two appendices.

Conclusion: The shape-distortion effects were studied relative to the desired parabolic reflector shape associated with uniform pressure forming of initially flat, circular membranes supported only at the edges, and have related these surface-distortion effects primarily to variations in focal length over the membrane surface. Based on the analysis results

obtained, and the assumptions defined in more detail in the report, the following major conclusions were reached:

- Pressure-loaded membranes tend to be spherical in shape, which sometimes can closely approximate an ideal parabolic surface. A close approximation for larger f_o/D 's⁽¹⁾ is the sphere, but for very small f_o/D 's this approximation becomes increasingly poor. Elastic membranes are always flatter in the center region and more sloped near the outer radius than the perfect sphere that has the same curvature at the membrane center. In addition, the spherical shape, which is approached with plastic deformation, always has more curvature (i.e., lower radius of curvature and shorter focal length) at the outer radius than does the nominal perfect sphere. Thus, it appears that the sphere is the best approximation to approach with the elastic/plastic forming of the metal membranes that are uniformly pressure loaded.
- When the membrane responds elastically, the degree to which the final shape approximates a spherical surface depends on both f_o/D and the dimensionless stiffness parameter (modulus x membrane thickness/initial tension = Et/T_o). Shapes that are nearly spherical and that approximate the ideal parabola quite closely can be attained with totally elastic membrane systems if $f_o/D > 2.0$ and if Et/T_o is small. When Et/T_o is large, then nonuniform tension states in the membrane can cause unacceptable distortions. Further, if Et/T_o is large, the required f_o/D for acceptable surface contours may grow appreciably above 2.0 to limit the distortions caused by elastic material response. Further, if $f_o/D < 2.0$ even when Et/T_o is small, the disagreement between the sphere and parabola can be a concern from an optical performance perspective.
- Figure S-1 shows findings with respect to pressure forming an initially flat membrane to a specific f_o/D and facet size. For optical elements having $f_o/D > 10$ that are typical of heliostat designs, elastic designs resulting in good parabolic surfaces appear to be feasible. Also for f_o/D 's < 10 , elastic distortions start to become a concern with many metal membrane designs, but good elastic contours using polymer membranes may be possible for f_o/D values somewhat below 3.5. Further, inelastic designs are required for steel, aluminum, and many polymer designs for f_o/D values below approximately 3.5, 2.0, and 1.0, respectively. Moreover, for optical elements with $f_o/D < 2.0$, the number of small-diameter optical facets required to approximate a large area, single-facet dish with $f_o/D = 0.6$ is small and decreases with decreasing f_o/D . Conversely, for reflector elements with $f_o/D > 2.0$, the facet size decreases and the number of facets required to produce a given concentrator

area increases. Finally, for nominal f_o/D 's < 1.5 , focal length variations relative to the parabolic shape become quite noticeable.

- Inelastic material response can lead to significantly smaller deviations from a perfect sphere than will elastic material response. This is because the plastic deformations will tend to relieve stress nonuniformities caused by elastic deformations and will thus make the stress distribution over the membrane surface more uniform; hence the membrane will become more spherical.
- The effect of work hardening on surface contour, which was considered in this study, did not appear to have a large deleterious impact on the surface contour, although for the cases studied, non-work-hardening material response always led to somewhat better focal-length uniformity. The major negative impact of work hardening appears to be due to the somewhat greater stress nonuniformity at the edge of the membrane when work hardening is present.
- A reduction of the forming pressure on a membrane that has undergone large plastic deformations results in worsening of the focal-length nonuniformity in the membrane center region with some increase in focal-length uniformity at the edge. It is possible, because of the area effect at large radii, that the overall optical performance may be improved. A more complete optical analysis is needed to verify this.

This report does not address the distortion effects caused by membrane seams, thickness nonuniformities, material anisotropy, and spatial modulus variations nor does it address those distortions caused by support frame displacements, rotations, and non-uniform and nonaxisymmetric pressures. Hence, these additional problems, when combined with the deleterious effects studied here, suggest that preforming of the membrane against a mandrel would be beneficial, especially if high-performance facets with $f_o/D < 1$ are required. However it is too early to rule out the potentially inexpensive pressure-forming technique. This is especially true if larger f_o/D facets, or if facets with less-stringent⁽²⁾ optical-quality requirements, are desired. Further, the potential benefits of nonuniform but axisymmetric forming loads may prove to be attractive. It is recommended that detailed optical analyses of the shape-distortion effects defined in this work be carried out. This will help ensure that the effects already identified will not prevent this forming approach from being applied to realistic designs.

(1) F_o is the focal length at the dish center and is sometimes referred to as the nominal focal length. D is the dish diameter.

(2)For example, such lower optical-quality facets may yield acceptable performance when combined with secondary concentrators.

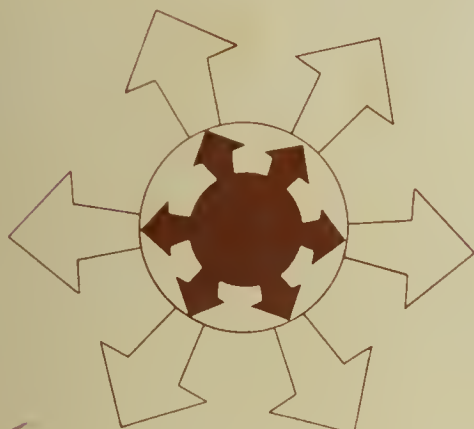
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Solar Energy Storage

Effective energy storage is critical to many solar technologies because of the problem of matching the energy available only during sunny daylight hours to the demand for energy that continues during cloudy days and at night.

Three basic types of thermal storage technologies have been identified: *sensible heat storage*, *latent heat storage*, and *reversible chemical reaction storage*. The first, sensible heat storage, is the simplest way to store thermal energy. Water is an excellent heat storage medium for low-temperature applications since it is inexpensive and has a high heat capacity. For air heating collectors, rocks are used. However, since rocks have a lower heat capacity than water and must have air spaces between them to allow passage of air, rock storage volumes must be considerably larger than those for water. At high temperature ranges, liquids such as heat transfer oils, molten salts, or liquid metals can be used.

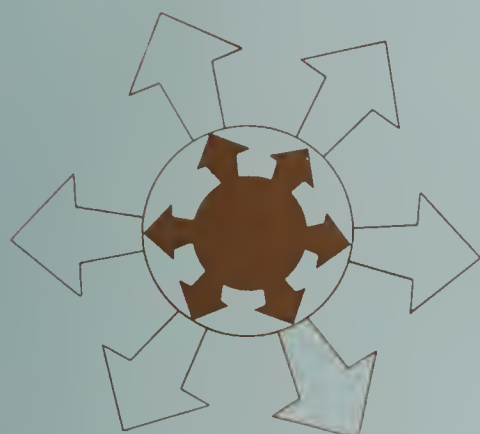
The second method of thermal storage makes use of the latent heat associated with a phase change, such as the transition that occurs when a solid melts to a liquid. For example, when ice melts to water it absorbs heat. Thus, solar heat can be stored by melting a solid substance that will serve as a storage medium for the solar energy. The energy can then be recovered when the medium solidifies. The primary advantage of this system is less volume. One such useful medium is known as Glauber's salt. This chemical compound stores more energy per volume than water. For limited temperature

excursions it takes eight times as much water as Glauber's salt for the same heat storage. However, there are a number of problems associated with the use of such salts which have been solved with varying degrees of success.

Thermal energy may also be stored as the energy which holds the components of a chemical compound together, known as bond energy. Such energy can be repeatedly stored and released by causing chemical reactions to change or recreate the compound. Chemical storage is attractive in cost since some of the materials are quite inexpensive. This method is also relatively immune to environmental conditions, and long-term storage is possible with minimal needs for thermal insulation. However, such technologies still require extensive research and development to become practical.

Storage of electrical energy is also possible. Batteries are the primary storage medium for electrical energy, and a number of light-weight, long-lived, and more efficient battery designs are under investigation.

Mechanical methods can be used for storage. These methods include pumped-hydro storage and compressed air storage. With the first method, water is pumped from a lower to a higher reservoir and then allowed to return to its original height when power is required. The latter method uses surplus power to compress air which can be expanded to produce energy when needed.



Solar Energy Storage

SERI Report Summary

Low Temperature Thermal Energy Storage: A State-of-the-Art Survey

Frank Baylin

Objective: Analyze activities in research, development, and demonstration of low temperature (below 250° C) thermal energy storage (TES) technologies having applications in renewable energy systems. Assess the status of TES technologies.

Discussion: This report provides an overview of low temperature TES technologies, summarizes contents and goals of the Department of Energy (DOE) and other programs leading to development and commercialization of low-temperature TES devices, catalogs and describes all recently completed and ongoing projects sponsored both privately and publicly, and generates comparative and summary information.

Storage technologies considered in the report have applications in heating and cooling of residential and commercial buildings and, to a certain extent, in agriculture and industrial processes. Three major categories of thermal storage are considered: sensible heat, phase change materials (PCM), and reversible thermochemical reactions.

Both short-term and annual TES technologies, based on principles of sensible heat, are discussed. Storage media considered are water, earth, and rocks. Annual storage technologies include solar ponds, aquifers, and large tanks or beds of water, earth, or rocks. PCM storage devices discussed in the report employ salt hydrates and organic compounds. The sole application of reversible thermochemical reactions outlined is for the chemical heat pump. In all cases, advantages and disadvantages associated with these technologies are contrasted. A brief summary of low-temperature TES applications is also presented.

A number of other technologies which can be classified as TES were excluded from this report. Two important omissions include photochemical storages (research sponsored by the Chemical Storage Program of the Division of Energy Storage) and open cycle chemical devices such as desiccant chillers (research sponsored by the System Development Branch of the Office of Solar Applications in DOE).

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SERI Report Summary

A Preliminary Screening of Thermal Storage Concepts for Water/Steam and Organic Fluid Solar Thermal Receiver Systems

Robert J. Copeland
Michael E. Karpuk
Jane Ullman

Objective: Document SERI systems analysis of several thermal storage concepts for water/steam receiver and organic fluid receiver systems.

Discussion: The objective of the study presented in this report was to compare alternative thermal storage concepts for two types of collector/receiver systems in two different applications.

A baseline solar thermal system design was selected for each application. A 100-megawatt plant designed by McDonnell Douglas was selected as representative of a water/steam/system in an electric power application. The Solar Total Energy Large-Scale Experiment at Shenandoah, Ga., which was designed by General Electric Corporation, was selected as representative of organic fluid systems.

Several alternative storage systems were designed for each of the baseline systems. The alternate systems were required to accept the charging and discharging fluid at the same rate as the baseline

storage systems. The alternate storage system designs included molten salt, dual-media molten salt, two-stage salt, and phase-change salt concepts. A total of seven alternate storage systems were designed for the water/steam receiver system and five for the organic fluid receiver system. Costs and performance for the baseline and alternate systems were calculated with the same set of algorithms.

Twenty-five figures and seven tables complement the text.

Conclusions: The alternate storage systems that are economically competitive require the use of a low-cost medium compatible with the working fluid of the system. Research to find such media is recommended. The phase-change concepts, though not economically competitive in the systems studied, offer significant potential increases in efficiencies for water/steam systems. Research is recommended in this area to solve cost problems.

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SERI Report Summary

Solar Ponds

T. S. Jayadev
Michael Edesess

Objective: Summarize analytic work on solar ponds performed at SERI during 1979.

Discussion: The report first describes the different types of solar ponds, including the nonconvecting salt gradient pond and various saltless pond designs. It then discusses the availability and cost of salts for salt gradient ponds and compares the economics of salty and saltless ponds as a function of salt cost. A simple computational model is developed to approximate solar pond performance. This model is used to size solar ponds for district heating and industrial process heat applications. For district heating, ponds are sized to provide space conditioning for a group of homes in different regions of the United States. An economic analysis is performed for solar ponds used in two industrial process heat applications. The use of solar ponds in the generation of electricity is also discussed.

Eight figures and ten tables are included.

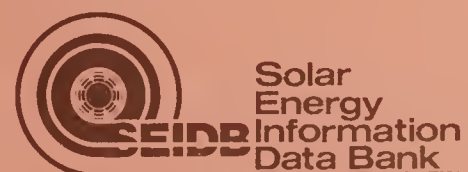
Conclusions: Solar ponds are probably the simplest and least expensive technology for conversion of solar energy to thermal energy. The solar pond is unique in its ability to act both as collector and storage. The cost of a solar pond per unit area is considerably less than that of any active collector available today. Solar ponds have the potential to displace significant quantities of fossil fuel in low-temperature heating applications in nonurban areas.

Solar ponds are competitive when conventional fuel sources are priced at \$5.00 per million Btu and are expected to rise in price at a rate of at least 10 percent per year. Total solar pond potential for displacing conventional fuel sources is estimated to be in the range from one to six quadrillion Btu per year in the near and intermediate future.

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SERI Report Summary

Preliminary Requirements of Thermal Storage Subsystems in Solar Thermal Applications

R. J. Copeland

Objective: Present methods of analyzing the value of thermal storage systems and ways of comparing various types of systems.

Discussion: To be useful, thermal storage systems must be cost-competitive with conventional fuel systems. A standard method to determine which solar systems are most cost effective avoids developing costly models of each. Simplified ranking methodology is used to conduct preliminary screening, and a computer version is used for comparing wide ranges of system parameters.

All data necessary to use the simplified method are included in the text, and a sample case is presented.

Conclusions: The ranking methodology compares thermal storage concepts on the basis of unit energy costs of the storage-coupled solar thermal system (i.e., busbar energy costs). The ranking methodology has been compared with absolute calculations of busbar energy costs. There are differences, but both approaches yield identical conclusions. Value derived costs are included for diurnal and long duration thermal storage in solar thermal electric power applications.

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SERI Report Summary

Issued June 1981

Central Unresolved Issues in Thermal Energy Storage for Building Heating and Cooling

C. J. Swet
Frank Baylin

Objective: Present major unresolved issues and discuss previous research in thermal energy storage for solar heating and cooling of buildings.

Discussion: This report explores the role of thermal energy storage technologies in improving or allowing the use of solar systems. Applications-oriented topics discussed include value-based ranking of storage concepts; temperature constraints; consistency of assumptions, nomenclature, and taxonomy; and materials screening criteria. Technology-related items covered include

seasonal storage concepts assessment, diurnal coolness storage, selection of hot-side storage concepts for cooling-only systems, phase-change storage in building materials, freeze protection for solar water heating systems, and phase-change storage for active solar space heating.

A list of key references and a bibliography are included. Nine tables and five figures complement the text.

Conclusions: No conclusions are cited in the report.

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SERI Report Summary

Issued June 1981

Systems Analysis Techniques for Annual Cycle Thermal Energy Storage Solar Systems

Frank Baylin
Sanford Sillman

Objective: Examine systems analysis techniques which are applicable for sizing and evaluating annual cycle thermal energy storage (ACTES) solar systems.

Discussion: ACTES solar systems can be modeled in a relatively simple fashion since storage and distribution system temperatures vary slowly over time. The key parameter in such efforts is average collector efficiency. This report discusses collector efficiency functions and methods for modeling ACTES solar systems. Methods are briefly outlined for investigating building loads based both on conventional and passive solar architectural design. Such aspects of system modeling as vali-

dation and thermal-versus-economic optimization are discussed. Two simple computer design codes for modeling ACTES solar systems are presented. Finally, U.S. Department of Energy programs for encouraging the development of ACTES solar systems are outlined.

Seven figures and five tables accompany the text.

Conclusions: A substantial number of straightforward analysis tools are available for sizing and evaluating ACTES solar systems. Several Department of Energy programs are directed toward systems analysis or management of ACTES solar systems.

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SERI Report Summary

Issued June 1981

Annual-Cycle Thermal Energy Storage for a Community Solar System: Details of a Sensitivity Analysis

Frank Baylin
Rosemary Monte
Sanford Sillman

Objective: Present the results of a simulation and sensitivity analysis of community-sized, annual-cycle thermal energy storage (ACTES) solar energy systems.

Discussion: An ACTES system employs a very large energy storage (typically enough to supply a month or more of space heat) and stores heat collected during the spring, summer, and fall to help supply the peak winter heat load. In this study, a SERI code was used to size systems in 10 U.S. cities, identify critical ACTES design parameters, and provide a basis for future studies. Three different building types (single buildings) and four different community sizes (50-, 200-, 400-, and 1000 units) were modeled. Two collector types (flat plate and evacuated tube) were modeled at two different tilt angles. A total of 44 systems were analyzed.

Thirty figures and six tables accompany the text.

Conclusions: Two linear relationships were derived which simplify ACTES system sizing. The average ambient temperature may be used to determine average yearly collector efficiency. Combined with estimates of space and domestic hot water (DHW) heating loads, storage and distribution losses, and total yearly insolation, the average yearly collector efficiency can then be used to estimate needed collector area. Additionally, storage size can be estimated from the winter net load which is based on space and DHW heating loads, storage and distribution losses, and collector solar heat gain for the winter months.

These algorithms can be further refined as results from the operation of ACTES solar systems become available.

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Solar Report Summary

Issued November 1982

Application of Solar Ponds to District Heating and Cooling

C. Leboeuf

Objective: Investigate the use of solar ponds for district heating and cooling applications.

Discussion: During fiscal year 1980, SERI conducted an investigation of solar ponds for district heating and cooling applications. Two locations were chosen for analysis: Fort Worth, Tex., and Washington, D.C. Only new neighborhoods typical of suburban subdivisions were considered. Solar ponds were then sized to meet space heating, cooling, and domestic hot water loads in each location for differing community sizes. Parameters such as storage layer temperature, pond geometry, and storage depth versus surface area were varied to determine the most effective approach to solar pond utilization. A distribution system was designed using commercially available components

which were sized according to engineering specifications. Trade-offs were considered for temperature, flow rate, pressure drops, and district layouts. Cost estimates were formulated for the systems using data generated in pond sizing and associated system costs.

Twelve figures and four tables are included.

Conclusions: Solar pond costs were found to be competitive with residential flat-plate collector systems, with delivered energy costs as low as \$16.00 per gigajoule.

Future studies should address energy supply to communities containing reduced-load houses in conjunction with a solar pond/district heating system.

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Solar Report Summary

Issued November 1982

Economic Analysis of Community Solar Heating Systems that use Annual Cycle Thermal Energy Storage

F. Baylin
R. Monte
S. Sillman
F. C. Cooper
J. D. McClenahan

Objective: Examine the economics of community-scale solar systems that incorporate centralized annual cycle thermal energy storage (ACTES) coupled to a distribution system.

Discussion: The economic analysis is based on a sensitivity analysis of a community-scale ACTES solar system. Three housing configurations — single-unit dwellings, ten-unit condominiums, and 200-unit apartments in complexes consisting of 50-, 200-, 400-, and 1000-basic units — were modeled in ten geographic locations in the United States. Two collector types were used for each configuration — flat plate and evacuated tube. Collector field areas and required

storage volumes were obtained for 44 configurations, and general sizing algorithms were derived. Study results are presented as normalized system costs per unit of heat delivered per building unit.

Two tables and 17 figures are included.

Conclusions: The analysis methods considered allow identification of the relative cost importance of each system component, and of the key variables that determine the optimum sizing of a district solar heating system. In more northerly locations, collectors are a larger part of system cost, while distribution networks are a larger proportion of the total cost in southern locations.

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Solar Report Summary

Issued November 1982

Optical Transparency of Inexpensive Salt Solutions for Construction of Density-Gradient Solar Ponds

John D. Webb

Objective: Describe a rapid laboratory measurement procedure for evaluating the solar transmittance of solutions of candidate salts and for estimating the solar transmittance of a given density gradient constructed using that salt.

Discussion: A major barrier to the commercialization of density-gradient solar ponds is the high cost of the salt used to produce the density gradient. The cost is a function of the purchase and transportation prices. Recently, new sources of salts available in bulk as industrial waste, have been found near sites proposed for solar ponds. Before these salts can be accepted for use in solar ponds, their environmental impact, ability to create a stable gradient, and solar energy transmission must be investigated.

The results of the measurement procedure may be used to estimate the necessary pond size to meet a set of thermal demands. The construction costs may then be weighed against the salt acquisition cost to select an optimum candidate from available salts.

The report describes the measurement apparatus and procedure, and presents a set of estimates for the performance of a flue gas desulfurization byproduct containing mostly sodium sulfate. An error analysis of

the measurement protocol, and an analysis of the effects of some trace contaminants on the transmittance of the salt solutions are also presented. Suggestions are given for improving the accuracy of the measurement procedure.

Six figures and twelve tables are included. An appendix gives the output data generated by computer program PON, which is used in estimating solar transmittance. The Fortran V code for this program is available upon request to the author.

Conclusions:

- Visible light transmittance of the upper layers of a gradient pond is a key performance-controlling parameter.
- In general, the pH of gradient-stabilized ponds should be kept high to allow transition metal ions to precipitate.
- The actual pond samples were only slightly less transparent than pure water in the visible region of the solar spectrum.
- Error analysis indicated that the results predicted for energy penetration to a pond storage layer, using a flue gas desulfurization salt gradient, were accurate to about plus or minus 12 percent.

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Solar Report Summary

Issued November 1982

Rapid Charging of Lead-Acid Batteries for Electric Vehicle Propulsion and Solar Electric Storage

Paul Longrigg

Objective: Present results of a study on rapid charging techniques for lead-acid batteries.

Discussion: Lead-acid batteries will continue to be used in both personal transportation and solar stand-alone storage roles until more exotic storage batteries become commercially available. Rapid charging of batteries is necessary in both the transportation and solar energy roles to provide flexibility and duration of operation for battery-propelled vehicles and to allow maximum storage of electricity for a photovoltaic array without shedding strings of photocells because of excess current capability. However, it is easy to overcharge lead-acid batteries, resulting both in fire hazards and economic penalties from reduced battery life.

This report surveys the various available charging techniques that have been used extensively, and

includes descriptions of newer techniques involving gas evolution-controlled charging. Fast charge approaches are evaluated, with an analysis of battery state equations — an important consideration in fast charge schemes.

Nineteen figures and two tables are included. An appendix treats the details of battery state equations.

Conclusions: Three prime parameters are of concern in the rapid charging of lead-acid batteries: time, reliability of charge, and battery lifetime. Of the rapid charging methods considered, the modified constant potential method and resistance-free voltage charging appear to be the most attractive, because of their relative simplicity and reliability. Gas-controlled techniques probably provide the least damaging rapid charge, but they are expensive and prone to failure.

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Solar Report Summary

Issued November 1982

A Survey of Sensible and Latent Heat Thermal Energy Storage Projects

F. Baylin
M. Merino

Objective: Briefly describe efforts toward developing new or improved thermal energy storage (TES) devices.

Discussion: Ongoing and completed research projects on sensible and latent TES for low-, intermediate-, and high-temperature applications are reviewed. Each project is presented in a standard format which includes project title; contractor name and address; funding source; monitoring laboratory; funding level and period; project status; project des-

cription; technical and economic parameters; and applications. The organization of the Department of Energy programs managing many of the projects is also outlined. The projects are organized into four sections: short-term sensible heat storage; seasonal sensible heat storage; latent heat storage; and models, economic analysis, and support studies.

Sixty-three figures and 24 tables are included.

Conclusions: No conclusions are cited.

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Solar Report Summary

Issued September 1983

Behavior of Nine Solar-Pond Candidate Salts

Daniel Schell
Cecile Leboeuf

Objective: To determine experimentally the suitability of nine salts for use in a salt-gradient solar pond, based on their thermal stability.

Discussion: Purchasing and transporting salt are two of the most expensive items in the construction of salt-gradient solar ponds. The economics of solar ponds could be improved by using alternative salts that can be obtained free or at low cost. One such salt is sodium sulfate, which is expected to be widely available as a flue-gas desulfurization waste product.

In this study, several highly soluble salts were tested for their suitability as solar pond materials in a laboratory salinity gradient pond. The salts tested were sodium chloride, sodium sulfate, sodium carbonate, sodium bicarbonate, magnesium chloride, calcium chloride, potassium chloride, potassium nitrate, and ammonium nitrate. Each of these salts has the potential to become a cheap, widely available resource. The behavior of the laboratory pond was monitored during testing of each alternative salt. Each salt's performance was compared with the performance of

sodium chloride, the most commonly used salt in ponds. Predictions of stability were made and compared with experimentally derived stability as determined by the growth of convective layers. The investigators observed good agreement between experimental and theoretical ranking of the stability of each salt. However, it was apparent that more extensive information on the properties of candidate salt solutions was needed.

Conclusions and Recommendations: Sodium sulfate, sodium carbonate, magnesium chloride, and calcium chloride exhibited greater stability than sodium chloride at the same concentration gradient. Ammonium nitrate, potassium nitrate, and potassium chloride showed less stability than sodium chloride at the same concentration gradient. These three salts are soluble enough to achieve the same stability as sodium chloride, but only if the concentration gradient is increased. Because of its low solubility, sodium bicarbonate was much less stable than sodium chloride and is, therefore, probably unsuitable for an unsaturated salt-gradient pond.

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Solar Report Summary

Issued September 1983

Conceptual Design of the Truscott Brine Lake Solar Pond System

Volume I

Utility-Independent Scenario

SERI Truscott Brine Lake Task Force

Objective: Present a conceptual design for a series of solar pond systems to provide pumping power for chloride control in the Red River Basin in Truscott, Texas.

Discussion: In this chloride control project, briny water will be diverted to avoid pollution of potable water. The diverted brine will be stored in a dammed natural basin where evaporation will concentrate the brine to the required salinity for a solar pond. The brine will be transferred to the solar ponds and injected at the proper levels to establish the necessary gradients and storage layers. Heat will be extracted from the ponds and used to drive organic Rankine-cycle (ORC) turbine generators. The electricity produced will serve the pumping needs of the chloride

control project.

The conceptual design presented in this report includes a performance analysis; a layout of the evaporation and solar ponds, the powerhouse, piping and heat exchangers; an operational strategy; specifications for major components; a cost estimate for the pond-related components and construction; and an estimate of operation and maintenance costs.

Thirty-two figures and 23 tables are included.

Conclusions: Five solar ponds totaling 54 ha with eight 300-kWe ORC turbine generators would serve the power requirements of the Truscott pumping stations.

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Solar Report Summary

Issued September 1983

Heat Rejection and Energy Extraction Within Solar Ponds

Yogesh Jaluria

Objective: To study the thermal and fluid process underlying heat rejection to the surface and energy extraction from the storage zone of a salt gradient solar pond.

Discussion: A study of the heat transfer and fluid flow process governing heat rejection to the surface layer of a solar pond and energy extraction from the storage zone has been carried out. The literature available on this and other related problems was studied in detail to determine the nature of the recirculating flows that arise and the effect they might have on the stability of the gradient layer. Simplified analytical models were considered to determine the governing parameters and their effect on the performance and efficiency of the solar pond. Estimates were made of the surface temperature rise and the increase in evaporation caused by heat rejection. Two flow configurations, end-to-end (inlet, top; outlet, diametrical top) and top-to-bottom (inlet, top; outlet, diametrical bottom) were considered for every extraction and the spread of the flow in the storage zone was studied. It was found that the limited penetration of the top-to-bottom configuration restricts its satis-

factory operations to small ponds. The experimental modeling of the flows under study was considered in terms of the governing parameters and it was found that the top-to-bottom configuration cannot be uniquely modeled. The choice of these parameters for a full-size pond is also discussed.

Twenty-three figures and two tables are included.

Conclusions: The gradient layer in a solar pond can be maintained with a negligible effect from intralayer recirculating flows if the flows are spread over the width of the pond, a suitable diffuser height is taken to reduce the flow velocities, and the diffusers are located as far as possible from the interface with the gradient zone. The flow and thermal fields are governed by two important parameters, the Reynolds number and Froude number. Heat rejection to the surface layer results in acceptable increases in temperature and evaporation. The end-to-end configuration (inlet-outlet at top and diametrical) for energy extraction is satisfactory for large ponds and the top-to-bottom one (inlet at top, outlet at bottom and diametrical) for smaller solar ponds.

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Solar Report Summary

Issued May 1984

High Temperature Integrated Thermal Energy Storage System for Solar Thermal Applications

A Subcontract Report for Solar Energy
Research Institute

A. P. Bruckner

A. Hertzberg

Aerospace and Energetics Research Program
University of Washington

Objective: To demonstrate the technical and economic feasibility of a novel, very high temperature solar thermal energy storage system that uses molten slag as the storage medium. This system produced power through a Brayton-cycle powered electric generator.

Discussion: The report contains discussions of the candidate storage materials, energy storage system, and economic analyses, as well as detailed supporting material provided in the appendices.

Metal oxides were investigated for use as storage media, but they were rejected because their melting points were too high. A slag bead aggregate was selected as the storage medium because of its desirable physical properties and low cost.

Absorbing energy directly into the heat storage material in the central receiver leads to a storage method that is very easily integrated with the power cycle. The process is envisioned to work as follows. Slag bead aggregate is melted in a solar central receiver and stored in liquid form at 1650 K in an insulated refrac-

tory storage vessel. Sensible heat is extracted from the molten slag in a direct-contact droplet heat exchanger, in which the slag is sprayed as a multitude of droplets through a high-pressure counterflowing working gas. The heated gas is used in a high-temperature regenerative Brayton cycle. The solidified slag droplets are returned to the solar receiver to repeat the cycle.

Seventeen figures and fourteen tables are included.

Conclusions: The α -alumina liner material used in the storage tanks, the ten slag pumps, and the droplet heat exchanger make this a very expensive system. Although the cost of the slag storage medium is very low in comparison with other storage medium, the overall storage system based on molten slag is more costly than other thermal storage technologies at all storage capacities considered. However, the molten slag storage system can store and use heat at much higher temperatures than any other storage concept. Research is needed to lower the cost of insulation and slag pumps, as well as to analyze further droplet formation and heat transfer rates with multiple droplets.

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Solar Report Summary

Issued June 1986

Solar Pond Research at the Los Alamos National Laboratory

G. F. Jones
K. A. Meyer
J. C. Hedstrom
D. P. Grimmer

Objective: Describe the solar pond research conducted at the Los Alamos National Laboratory (LANL).

Discussion: The solar pond research program at LANL uses a coordinated experimental, numerical, and analytical program to obtain a thorough understanding of pond fluid dynamics.

This publication discusses the main issues in the theory of solar ponds including the interfacial-boundary-layer model, models for interface motion and pond performance, ground heat loss, and heat extraction. Central to the program is the development of a one-dimensional computer model that is capable of accurately predicting time-dependent solar pond temperatures, interface motion, and salinities. The

report describes the computer model, as well as the experiments that were designed and performed to validate it. The experiments include two laboratory tanks in which temperature, salinity, data and flow-visualization are obtained and a 232-m² outdoor solar pond. A section on the theory of solar ponds is also included, along with an explanation of nomenclature and equipment.

This publication contains 4 tables and 25 figures.

Conclusions: Results from the preliminary validation show good agreement between the pond's predicted dynamic behavior and that which actually occurred in the experiments, although more validation using data from full-sized solar ponds is needed.

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Solar Report Summary

Issued June 1986

Doubly Diffusive Linear Stability with Nonconstant Gradients

F. Zangrando

L. Bertram

Objective: Present the results of a numerical analysis (by expansion in Fourier series) that was performed on the effect of variable stratification on the linear bifurcations of a doubly diffusive plane parallel layer.

Discussion: Because the motivation is to analyze salt-gradient solar pond stability, a Prandtl number of 7 and a ratio of diffusivities of $1/80$ is used in the study, with (large) solute Rayleigh numbers (R_s) ranging from 10^4 to 10^{12} . Stratification of the solute is cubic, antisymmetric about the midlayer; because temperature has a higher diffusivity, it is given a linear stratification. The exchange of stability results also solves the "fingering" and thermal problems with cubic stratification.

The report includes 16 figures; it also presents 2 appendices that deal with the numerical solution of equations.

Conclusions: For the overstable case, the numerical results approach Walton's perturbation solution at large R_s but differ significantly at smaller R_s ($<10^8$). While the exchange of stabilities and the overstable modes both display an expected tendency to localize about the point of minimum solute gradient, the overstable modes behave in other nonintuitive ways. Sublayers of reversed salinity gradient, if small enough, can be stable. Above R_s of 10^{12} , computations become prohibitively expensive as a continuous spectrum is approached. A simple sublayer-scaling rule defines an infinite family of R_s and stratification parameters on which the localized eigensolution is nearly invariant.

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Solar Report Summary

Issued December 1986

Objective: Describe alternatives to ASHRAE Standard 94-77 and examine the advantages and disadvantages of each alternative.

Discussion: The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has responsibility for developing various National Voluntary Consensus Standards for use in the heating, refrigeration, and air conditioning industry. ASHRAE Standard 94-77, "Method of Testing Thermal Storage Devices Based on Thermal Performance," was developed to allow manufacturers of thermal energy storage devices to compare their products. However, ASHRAE Standard 94-77 has several inadequacies when applied to latent-heat devices. Alternatives to Standard 94-77 are the focus of this publication.

The report describes two proposed methods in detail: (1) the Yu Lwin method, developed at Argonne National Laboratory (ANL), and (2) the ASHRAE method, recommended to Project Committee SPC 94.1. The experiments performed with each method are described, along with the results of these experi-

Comparisons of Testing Methods for Latent-Heat- Storage Devices

R. L. Cole
J. R. Hull
Y. Lwin
Y. S. Cha

ments. Additionally, a comparison of the two proposed methods is presented, as are other possible test methods.

The publication contains 12 tables and 43 figures. Four appendices are also included. They present preliminary procedure for testing latent-heat thermal energy storage units for solar applications, a parameter analysis of a constant-temperature input method, a constant-heat input test method, and a parameter analysis of a constant-heat input method.

Conclusions: Considerable work remains to be done before a fully usable standard is achieved. The difficulty of incorporating the energy from auxiliary sources into calculation results needs investigation. Also, more experience with different types of systems is needed.

Of the two proposed standards considered in this report, the authors recommend that the ASHRAE method, with some modifications, be used as a basis for further development of a testing procedure.

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Wind Energy

Wind is considered a solar energy resource because it is caused by the sun's uneven heating of the earth. Wind represents kinetic energy which can be converted by windmills into mechanical motion or by wind turbines into electricity.

Windmills have been used for agricultural purposes since the 9th century. Some six million small Wind Energy Conversion Systems (WECSs) operating in the United States in the past, were used mostly for pumping water and generating electricity. The availability of cheap electricity and other relatively inexpensive energy sources ended many uses of WECSs, yet an estimated 150,000 wind systems still operated in this country in the 1970's.

Today, renewed interest in both large and small-scale WECSs for producing electrical and mechanical energy may mark the beginning of another important era for wind energy. Currently, research and development on both large and small wind turbines is being pursued by both private and governmental interests.

Most wind systems have horizontal or vertical propellers with two, three, or more blades, however, other innovative machines are being researched and tested. The basic WECS consists of propeller-

type rotor blades that rotate in response to the wind. The rotor turns a low speed shaft which is connected to a gearbox. The gearbox converts the relatively low speed rotation of the rotor into the high speed rotation necessary to drive a electrical generator.

The largest wind machines have blades as long as the wing span of a jumbo jet and weigh many tons. Components of fiberglass, steel, aluminum, concrete, wood, plastics, and other materials are used. Deployment plans range from units for a single home to wind farms with capacities of some fossil fuel generating facilities.

Wind is a random resource due to fluctuations in wind speed and direction which may occur as frequently as several times a minute. Also, wind speed and wind characteristics can differ greatly over short distances. Changing weather patterns and shifts in climate mean changes in the availability and intensity of the winds. Nevertheless, wind power is a viable alternative energy resource. Construction of wind energy installations does not require new techniques, and cost estimates in regions with favorable winds are close to those of other energy sources.

SERI Report Summary

A General Reliability and Safety Methodology and Its Application to Wind Energy Conversion Systems

Michael Edesess
Robert D. McConnell

Objective: Develop a Reliability and Safety Program (RASP) which computes the effect of inspection schedules on safety and system availability, and calculates costs for system inspections and repairs.

Discussion: In conventional system reliability calculations, each component may be in the operable state or the under-repair state. Such calculations are used to determine system unavailability, or the probability of the system being down for repairs. By introducing a third component state—defective, but defect undetected—the methods developed in this report enable system safety projections to be made in addition to availability projections. A RASP which computes the effect of inspection schedules on safety and availability and calculates costs for system inspections and repairs is presented in detail. RASP is applied to a hypothetical, simplified wind energy conversion system.

Three figures and three tables complement the text.

Appendix 1 presents a sample output from RASP. Appendix 2 is a listing of the RASP program.

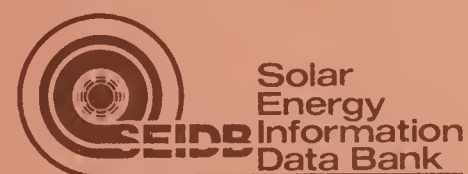
Conclusions:

- The RASP program can be used to determine both system availability and the probability of catastrophic system failure.
- By defining the sensitivity of these statistics to changes in the reliability of individual components, the RASP method can be used to identify critical components, thus aiding in decisions related to: inspection and maintenance schedules, component durability, and system redundancies.
- RASP is a general program which would be useful for any system where reliability and safety are major concerns.

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SERI Report Summary

Wind Resource Analysis—Annual Report

Donald M. Hardy

Objective: Describe the FY78 results of the Wind Resource Analysis task of the SERI Energy Resource Assessment Branch (ERAB).

Discussion: According to the report, initial steps were taken by ERAB to acquire modern atmospheric models of near-surface wind flow and primary data sets used in previous studies of national and regional wind resources. The models and data sets acquired are described.

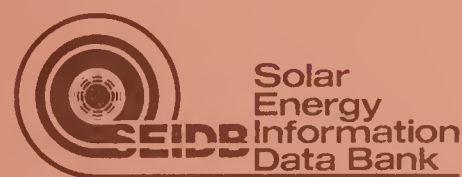
Conclusions:

- Due to numerous assumptions used, previous wind energy studies differ considerably in their conclusions.
- State-of-the-art atmospheric models are necessary in SERI wind research, but they need to be tested and verified in diverse applications.

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SERI Report Summary

Economics of Selected WECS Dispersed Applications

Stella Krawiec

Objective: Present an economic analysis for distributed wind energy conversion systems (WECS).

Discussion: This report examines:

- the cost of electricity generated by selected wind energy systems in residential and agricultural applications,
- the break-even cost of wind systems that are economically competitive with conventional power sources, and
- the impact of major economic factors on the cost performance index of such systems.

Two major economic measures used in the analysis are break-even period and levelized cost (life-cycle cost) of electricity.

The cost performance index used is for a dispersed application of a commercially available ten-kilowatt wind turbine generator. All-electric homes consuming more than 15,000 kilowatt-hours annually are used in the analysis. The agricultural application is

a commercial poultry and egg farm using over 92,000 kilowatt-hours of electricity annually.

The following parameters are considered for the impact of major economic factors on the cost performance index of WECS: installed cost of WECS, cost of electricity from conventional sources, evaluation rates for the price of electricity, capacity as a function of system performance and wind velocity, and wind energy output.

Fourteen figures and six tables are included.

Conclusions:

- In areas with high wind resources or high conventional fuel prices (Alaska, Hawaii, and New England), small-scale WECS appear to be economically viable.
- Significant reductions in wind system energy costs are required to make these systems generally cost-competitive with conventional energy sources.
- The economic feasibility of WECS should increase as conventional fuel prices climb and as WECS prices decline.

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SERI Report Summary

Capital Formation for Small Wind Energy Conversion System Manufacturers

Final Report

A Guide to Methods and Sources

Peter H. Smeallie
Benjamin Wolff

Objective: Describe sources of capital for small wind energy system manufacturers.

Discussion: In September 1979 the American Wind Energy Association, with the support of SERI, convened a two-day workshop in Boulder, Colo., to address the issues of capital formation and the small wind energy conversion systems (SWECS) community. The workshop brought together representatives of the financial community and of the SWECS industry to identify key concerns associated with capital formation and to develop useful suggestions about ways for SWECS manufacturers to bridge the gap between the capital market and the wind industry. This report is based on the material presented at the workshop. In addition to discussing the different terms and conventions used in the financial community, the report discusses the importance of a comprehensive business plan. The procedure for formulating such a plan is presented in detail. Finally, case histories of four wind companies' experiences in raising capital are included.

Three appendices list the workshop participants, the workshop agenda, and acknowledgment.

Conclusions:

- The SWECS community consists of two main groups—manufacturers that are

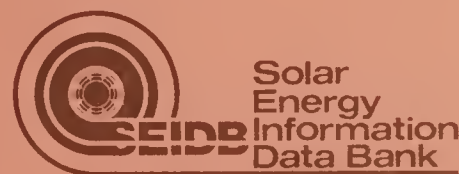
subsidiaries of larger corporations and individuals trying to set up their own businesses. The capital formation problems for the two groups differ substantially and must be approached accordingly:

- The SWECS industry is a high technology industry in its embryonic phase.
- The impacts of government actions in the marketplace are more acutely felt in the SWECS industry than in established industries.
- Most SWECS manufacturers are currently in the seed stage or start-up stage.
- A well-developed business plan is essential for a SWECS firm.
- Management and good personnel are the most valuable assets a new SWECS firm can acquire.
- The financial community should recognize the embryonic nature of the SWECS industry and should devote more time and effort to the technical evaluation of a SWECS proposal.
- The government must clearly define the regulatory environment in which SWECS manufacturers will operate.
- Government programs to assist small businesses should be encouraged.

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SERI Report Summary

Issued June 1981

Preliminary Technical and Economic Evaluation of Vortex Extraction Devices Final Report

T. R. Kornreich
R. J. Kottler, Jr.
D. M. Jennings

Objective: Critically evaluate two vortex wind energy extraction devices: the Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC).

Discussion: The TWES and VAC were evaluated to determine their technical and economic viability in comparison with conventional horizontal axis wind energy systems. The basis used for the economic comparison in this study is the energy cost that could be achieved by "mature product" versions of the TWES or VAC, and conventional systems.

Previous experimental work has dealt with very small-scale wind tunnel tests so that available data cannot be used with confidence to resolve uncertainties or to estimate full-scale system performance. However, even if all the technical uncertainties were resolved for the TWES, its energy cost

would be considerably greater than that of conventional systems.

The VAC is not subject to as many technical uncertainties as the TWES, but still presents problems such as vortex breakdown that need to be experimentally evaluated. Field test data on the VAC were not available for this study. However, even under the best conditions, the cost of energy from the VAC would be much greater than that from conventional systems.

Sixteen figures and 18 tables are included. An appendix treats structural analysis of the TWES.

A companion report, SERI/TR-8003-2, summarizes this study.

Conclusions: It appears that neither the TWES nor the VAC can be economically competitive with conventional horizontal axis wind systems.

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SERI Report Summary

Issued June 1981

Preliminary Technical and Economic Evaluation of Vortex Extraction Devices Summary Report

T. R. Kornreich
R. J. Kottler, Jr.
D. M. Jennings

Objectives: Summarize a critical evaluation of two vortex wind energy extraction devices: the Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC).

Discussion: The two systems were evaluated to determine their technical and economic viability in comparison with conventional horizontal axis wind energy systems. The basis used for the economic comparison in this study is the energy

cost that could be achieved by "mature product" versions of the TWES or VAC, and comparable conventional systems.

Seven figures and five tables are included. A companion report, SERI/TR-8003-1, contains the full evaluation and detailed results.

Conclusions: It does not appear that either the TWES or VAC could achieve economic parity with conventional horizontal axis wind systems.

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SERI Report Summary

Issued June 1981

A Definitive Generic Study for Sailwing Wind Energy Systems Non- Technical Summary Report. Final Report

Kurt H. Hohenemser
Andrew H. P. Swift
David A. Peters

Objective: Determine whether sailwing wind energy conversion systems have the potential of being cost-effective energy resources.

Discussion: The sailwing concept was applied by Princeton University and other organizations to the construction of rotary wings for windmills. Performance data was collected for 11- and 13-foot rotor models constructed at Princeton.

A new method of performance and cost optimization for wind turbines was used to evaluate the sailwing concept. The method is based on assigning two non-dimensional design parameters to the wind turbine. The first parameter relates rated generator output power to the yearly average wind velocity at the site. The second, applicable only to constant rotor speed operation, relates the blade tip speed to the first parameter. This non-dimensional treatment has the advantage that fewer parameters are involved in the optimization process, and that the results apply to all sizes of wind turbines. Thus, it is possible to compare performance and cost-effectiveness of the 25-foot Grumman wind machine with the 125-foot diameter NASA MOD-OA wind machine.

The technical discussion covers the fundamentals of sailwing design, tests and models applicable to the concept, and the dynamics of sailwing wind machines. Different configurations of sailwing machines are discussed, as well as potential improvements that can be made. Finally, size limitations and cost analysis are covered in detail.

Forty-nine figures and nine tables complement the text. A nomenclature list is included. Appendix A covers optimization of output for wind machines, and Appendix B treats power train dynamics. This report is identical to the report SERI/TR-8003-02.

Conclusions: The non-dimensional analysis showed that sailwing machines can have about the same capacity factor and initial cost factor as optimized NASA MOD-OA machines if properly optimized for a given site. The rotary sailwing concept should provide an acceptable alternative to conventional wind machines.

Further government support of rotary sailwing system research should aim to:

- clarify whether measurements on a moving test bed are usable without correction,

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- design and build test equipment where the rotor speed is kept approximately constant,
- monitor over extended periods of time the performance of the Grumman 25-foot diameter sailing rotor,
- conduct tests with rotary sailwings using heavier industrial cloth with silicon rubber protection to determine whether longer lasting fabrics are useful for sailing application, and
- test wind rotor model performance either in a wind tunnel or with a moving test bed at a reasonably high Reynolds number and with a number of different rotor configurations.

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SERI Report Summary

Issued June 1981

A Definitive Generic Study for Sailwing Wind Energy Systems Final Report

Kurt H. Hohenemser
Andrew H. P. Swift
David A. Peters

Objective: Determine whether sailwing wind energy conversion systems have the potential of being cost-effective energy resources.

Discussion: The sailwing concept was applied by Princeton University and other organizations to the construction of rotary wings for windmills. Performance data was collected for 11- and 13-foot rotor models constructed at Princeton.

A new method of performance and cost optimization for wind turbines was used to evaluate the sailwing concept. The method is based on assigning two non-dimensional design parameters to the wind turbine. The first parameter relates rated generator output power to the yearly average wind velocity at the site. The second, applicable only to constant rotor speed operation, relates the blade tip speed to the first parameter. This non-dimensional treatment has the advantage that fewer parameters are involved in the optimization process, and that the results apply to all sizes of wind turbines. Thus, it is possible to compare performance and cost-effectiveness of the 25-foot Grumman wind machine with the 125-foot diameter NASA MOD-OA wind machine.

The technical discussion covers the fundamentals of sailwing design, tests and models applicable to the concept, and the dynamics of sailwing wind machines. Different configurations of sailwing machines are discussed, as well as potential improvements. Finally, size limitations and cost analysis are covered in detail.

Forty-nine figures and nine tables complement the text. A nomenclature list is included. Appendix A covers optimization of output for wind machines, and Appendix B treats power train dynamics. This report is identical to the report SERI/TR-98003-05.

Conclusions: The non-dimensional analysis showed that sailwing machines can have about the same capacity factor and initial cost factor as optimized NASA MOD-OA machines if properly optimized for a given site. The rotary sailwing concept should provide an acceptable alternative to conventional wind machines.

Further government support of rotary sailwing system research should aim to:

- clarify the question whether measurements on a moving test bed are usable without correction,

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- design and build test equipment where the rotor speed is kept approximately constant,
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heavier industrial cloth with silicon rubber protection to determine whether longer lasting fabrics are useful for sailing application, and

- test wind rotor model performance either in a wind tunnel or with a moving test bed at a reasonably high Reynolds number and with a number of different rotor configurations.

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SERI Report Summary

Issued June 1981

A Definitive Generic Study of Augmented Horizontal Axis Wind Energy Systems Executive Summary. Final Report.

Peter B. S. Lissaman
Bart Hibbs
Stel N. Walker
Thomas Zambrano

Objective: Present the results of a cost-effectiveness study of three different types of wind turbine augmentors.

Discussion: One method of increasing the power output of a wind turbine is to add an augmentor system that will act like a converging duct to increase the wind velocity at the turbine disk and thus increase the energy flow through the device. The cost-effectiveness of such systems depends upon the trade-off between the additional energy output and the added cost of the augmentor system.

Three types of augmentors were considered: two passive and one active. Of the passive devices, one has an augmentor, which is a duct surrounding the turbine actuator (axisymmetric static); and the other has a delta wing in the vicinity of the actuator (planar static). In the third system, the augmentor consists of moving airfoils (tip-vanes) attached to the rotor.

Analytical and experimental data were used to compute the aerodynamic performance of each augmentor. Then the systems were sized to give the same performance and power output in a given wind as the NASA MOD-X wind turbine. Finally, the cost of power in cents per-kilowatt-hour was calculated for each system. A standard SERI formula was used that included capital cost, operations and maintenance cost, annual cost rate, and annual energy produced.

Eleven tables and 13 figures are included, as well as a table of nomenclature.

Conclusions: The dynamic augmentor produced the best cost figures, having a power cost about 1.2 times that of the MOD-X. The best axisymmetric static system gave a cost ratio of 1.8, and the best planar static system had a ratio of 3.0. All the augmentor systems appeared less cost-effective than the plain MOD-X, although the dynamic augmentor merits further attention.

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SERI Report Summary

Issued June 1981

A Definitive Generic Study for the Effect of High Lift Airfoils on Wind Turbine Effectiveness Executive Summary. Final Report.

Peter B. S. Lissaman
Robert E. Wilson
R. W. Thresher
Stel N. Walker

Objective: Examine the effect of high lift airfoils on the cost-effectiveness of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) machines.

Discussion: First, a generalized formula was developed for the performance of modern airfoils in terms of lift, drag, and thickness at appropriate Reynolds numbers. Single-element, multi-element, symmetrical, extra-thick airfoils, and jet flap airfoils were analyzed. Then the effect of the above airfoils on the performance of a variety of wind turbines was studied. For HAWTs, the MOD-X machine was used as a baseline. For VAWTs the Sandia Optimization Code was used to obtain a baseline.

Seven figures and one table are included in the

report. Four appendices present detailed technical information.

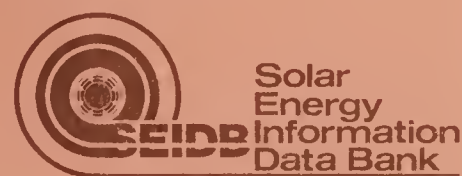
Conclusions:

- Airfoil selection is important in rotor design.
- High lift capability is less important than airfoil thickness.
- Exotic airfoils show little promise.
- New structural approaches, different from the single element cantilever blade, have good prospects.
- Improved high lift airfoils can increase cost-effectiveness about 10 percent.

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SERI Report Summary

Issued June 1981

Augmented Horizontal Axis Wind Energy Systems Assessment Executive Summary. Final Report.

Tetra Tech, Inc.

Objective: Examine the effectiveness of augmentor systems for horizontal axis wind turbines (HAWT).

Discussion: Three devices are examined, in which an augmentor surface is used to increase the mass flow through a turbine and thereby increase the turbine's power output per unit rotor disc area. The three devices are the dynamic inducer, in which tip vanes on a conventional turbine induce increased flow through the rotor; the diffuser augmented wind turbine (DAWT), in which a diffuser reduces pressure behind the turbine to increase flow through the turbine; and the vortex augmentor concept (VAC), in which the augmentor surface is a highly swept delta wing.

Performance (annual energy output) and costs (both investment and maintenance and operations costs) are calculated for the augmented systems, and compared to those of conventional systems.

Five appendices provide detailed data and background information.

Conclusions: The DAWT with a ferrocement, fiberglass, or aluminum diffuser shows the most potential. The VAC probably is not competitive with conventional systems, but performance data are incomplete. Additional research is needed on augmentation ratios and on the economics of diffusers built of ferrocement, fiberglass, and aluminum.

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Solar Report Summary

Issued November 1982

Boundary Layer Mesoscale Wind Analysis

Amir Mikhail

Objective: Describe the data collected from the Prototype Regional Observing Forecasting Service (PROFS) network by the National Oceanic and Atmospheric Administration (NOAA) and suggest a method of analyzing these data to determine mesoscale wind velocity variability.

Discussion: The network consists of 20 stations distributed over 51,800 km² (20,000 mi²), with wide variations in topography and surface cover. Other sources of data, such as the National Climatic Center (NCC) and the NOAA Erie, Colorado, meteorological tower, have been identified as supplements to the PROFS network. The additional data have permitted the creation of a high-resolution, high-density mesoscale network.

A method of analyzing the mesoscale variability of the wind resource is suggested. The analysis is based on

mesoscale parameters that influence the transfer of momentum in the surface layer. These parameters are site elevation, distance from the coast, angular horizon, surface roughness length, thermal stability, shape of the surrounding topography, and geostrophic wind. Various methods of evaluating these parameters have been detailed. The contribution of the parameters to mesoscale wind variability is analyzed.

This 29-page report contains six illustrations, including maps of PROFS sites in Colorado, and seven tables.

Conclusion: A model is proposed that can be used in analyzing an accumulated one-year of PROFS data, NCC data, and ERIE tower data if an additional source of funding is identified.

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Solar Report Summary

Issued November 1982

Environmental Noise Levels SVU MOD-2 Wind Turbine Test Sites at WPRS Medicine Bow, Wyoming

Edward McKenna
Carol Etter
Engineering Dynamics, Inc.

Objective: Document the acoustic output associated with the operation of large, utility-grade wind turbines by utilizing field measurements and existing analytical tools.

Discussion: In order to determine the overall effect of wind turbines on the acoustic environment, it is helpful to obtain data identifying preinstallation acoustic sources and their associated levels present at wind turbine sites. These environmental noise levels can then be used when the wind turbines are installed, as a reference to assess the overall impact of the wind turbines on the acoustic environment. At the request of the NASA Wind Energy Project Office, this report documents the environmental sound levels at the Department of Interior's Water and Power Resources

Services Wind Turbine Test Sites at Medicine Bow, Wyoming, in October 1980. This study will be used to compare acoustic levels measured after the planned and proposed wind turbines are installed to assess the acoustic impact of the turbines. The study has been performed in accordance with the guidelines set forth by the U.S. Environmental Protection Agency for establishing baseline acoustic environments.

Conclusion: The study shows that, typical of undeveloped rural areas, the sound levels recorded during the nighttime hours are 10 dB(A) below those recorded during the daytime. The two Wind Turbine Test Sites studied are described as quiet for the time period studied.

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Issued September 1983

The Application of U.S. Upper Wind Data in One Design of Tethered Wind Energy Systems

R. J. O'Doherty
B. W. Roberts

Objective: Assess the upper atmospheric wind resource for the continental United States, Hawaii, and Alaska.

Discussion: Using raw wind data from the National Center for Atmospheric Research, the probability distributions of wind velocity were computed for 54 sites, and detailed calm wind analyses were performed for five of these locations.

Following a brief introduction, the concept of applying wind data to tethered systems is discussed. The numerical techniques used are explained in detail, and the results of the analyses are presented.

Thirteen figures and two tables are included. Four appendices present average wind velocity and power values, probability distributions of wind velocity, annual calm-period charts, and a discussion of the use of the charts.

Conclusions: The average power density of the wind resource can be as high as sixteen kilowatts per square meter at northeastern U.S. sites. This power density is a maximum around the 300 millibar pressure level. The calm wind analyses show that on the average, the wind lulls about one day per week for a period in excess of about thirty hours.

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Predictions of Low-Frequency Sound from the Mod 1 Wind Turbine

R. Martinez
S. Windall
W. Harris

Objective: To determine if aerodynamic noise mechanisms are associated with the acoustic noise from the operation of the MOD-1 Wind Turbine located near Boone, N.C.

Discussion: Recent acoustic measurements indicate that sound from the turbine produced structural vibrations in homes near the turbine site. The possible sources of aeroacoustic noise studied in this report were steady blade loads, unsteady blade loads due to wind shear, and unsteady loads on the blades as they pass through the tower wake. Mathematical models

that were used to study these noise sources are described in this report.

Conclusions: The results showed that the most significant source of impulsive, low-frequency sound was the unsteady loads that occurred when the blade passed through the tower wake. This problem might be resolved by operating the turbine at a lower rotor speed and/or by changing the structural configuration of the tower to create an azimuthally smoother wake which would dramatically reduce the noise.

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Windmill Wake Turbulence Decay: A Preliminary Theoretical Model

E. A. Bossanyi

Objective: To develop a preliminary theoretical model of wind turbine wake turbulence decay to be used for assessing the acoustic noise that could be generated by a series of turbines operating downwind of each other in a cluster.

Discussion: The model described is at least partially based on the assumption of isotropy in the turbine wake turbulence. However, anisotropic conditions can exist, particularly in the near-wake region. Shear-generated turbulence may exist several rotor diameters farther downstream than the model indicates — a gradual development rather than the immediate decay assumed by the model. It is also important to identify the precise turbulent wave-

lengths responsible for acoustic noise production and model them accordingly.

Conclusions: Results must be considered as preliminary because of assumptions made for the model. Although turbine-generated turbulence will have decayed substantially by the time it reaches the next turbine in a cluster, the results indicate that there may be some energy remaining under certain atmospheric conditions at wavelengths that may be of concern for noise and structural reasons, notably low turbulence intensities and high wind speeds, particularly when atmospheric stability is not too great. This is most likely to happen in the morning or evening during the transition from daytime to nocturnal boundary layers, and vice-versa, particularly at more elevated sites where the winds tend to increase after dark.

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WECS Value Analysis: A Comparative Assessment of Four Methods

R. L. Sullivan
Theresa Flaim
David Percival

Objective: Compare four methods developed for conducting economic assessments of wind energy conversion systems (WECS) in utility applications.

Discussion: The assessment methods compared were developed under U. S. Department of Energy sponsorship by SERI (2 methods), the Aerospace Corporation, and the JBF Scientific Corporation. In order to isolate the effects of using different computer models, SERI, Aerospace, and JBF analyzed two case study utilities, Southern California Edison (SCE) and Consumers Power Company (CPC). To the extent possible, the three analysis teams used the same input data regarding the wind resource, wind turbine characteristics, generating units, load forecasts, fuel costs, and fuel cost escalation rates. The results were compared for the following phases of analysis: WECS performance analysis, load modification, production cost analysis, capacity displacement analysis, and break-even cost analysis.

Thirteen figures and 29 tables are included.

Conclusions: The four methods yield comparable results, especially for operating cost savings. Reduced operating cost will be the major determinant of the value of WECS to utilities with large amounts of oil or gas capacity; they accounted for over ninety percent of the total savings for both utilities studied. Estimates of operating cost savings associated with WECS were in good agreement among the methods for SCE, but operating cost savings varied more widely for CPC due to differences in the way that the different analysis teams modeled the large pumped hydro unit. Variations in the estimated WECS effective load-carrying capability were significant for both utilities.

Probabilistic techniques for characterizing wind generation should be used in assessing utility applications of WECS. For production cost modeling, simulations of pumped hydro capacity should be checked to ensure that the estimated operation is realistic.

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Solar Report Summary

Issued September 1983

Wind Power for Developing Nations

Amir S. Mikhail

Objective: Present information aiding assessment of the potential of wind energy conversion systems (WECS).

Discussion: This report presents an overview of the global wind resource, a survey of available wind-siting techniques, and site data adjustment methods.

Regression equations relating the average annual power output to wind-regime and machine characteristics are developed, and the results are compared with theoretical and empirical curves. The basic aerodynamic principles of calculating the forces and moments acting on WECS components are given.

A methodology is outlined for obtaining a match between machine and site characters for the most cost-effective power production.

A selected list of WECS and recording equipment available in the U.S. and abroad is given. Since

mechanical shaft output machines could replace animal and human muscle in developing countries and are easier to construct than high-speed electrical output machines, construction plans for a selected number of systems are presented. Lists of worldwide dealers, distributors, and manufacturers are given.

The final section of the report covers wind energy applications for rural development. In this section, applications are covered in three categories: electrical, direct heat, and pumping.

One hundred-fourteen figures and 38 tables are included. Appendix A presents plans for a low-cost windmill. Appendix B gives plans for a cheap water-pumping wind machine.

Conclusions: There exists great potential for WECS in developing countries, and the contents of this report should be valuable to planners, developers, and consumers.

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Solar Report Summary

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Acoustical Measurement of DOE/NASA MOD-0 Wind Turbine at Plum Brook Station, Ohio

C. L. Etter
N. D. Kelley
H. E. McKenna
C. Linn
R. Garrelts
Solar Energy Research Institute

Objective: To monitor the low-frequency acoustic emissions associated with the DOE/NASA MOD-0 Wind Turbine while its rotor operated in the normal position downwind of its support tower and in an upwind configuration.

Discussion: The DOE/NASA MOD-0 was employed to examine turbine rotor placement as a design criteria for minimizing low-frequency acoustic impulsive noise which has been associated with the larger, MOD-1 turbine in Boone, North Carolina. The ability of the MOD-0 to perform under a wide range of programmable and controllable experimental conditions

made it the ideal platform in which to study the effects of various design parameters on the production of acoustic noise.

Seventeen figures are included.

Conclusions: Under the available atmospheric conditions, an analysis of the low-frequency acoustic emissions associated with the MOD-0 rotor in its normal downwind position and in a reversed upwind configuration produced some evidence of impulsive acoustic behavior in the downwind mode at 35 rpm; but no such evidence was found at 23 rpm or in the upwind mode at either rotor speed.

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Aeroelastic Stability Analysis of a Darrieus Wind Turbine

David Popelka
Sandia National Laboratories

Objective: To develop a simple aeroelastic stability analysis for predicting flutter instabilities on vertical axis wind turbines.

Discussion: Tests on a scale model Darrieus wind turbine have shown that under certain conditions, the turbine may experience a flutter instability. Although flutter has not been observed on a full scale turbine, analysis is required to ensure the stability of future designs. This report describes the physical mechanism that creates flutter in Darrieus turbines. The

mathematical formulation of the problem and the analytical model are presented, and the theoretical results are compared with experimental data from the Sandia two-meter turbine.

Nine figures are included.

Conclusions: The aeroelastic stability analysis model appears to be an adequate design evaluation tool for assessing the probability of flutter on a Darrieus wind turbine.

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Analysis of the Effects of Integrating Wind Turbines into a Conventional Utility: A Case Study

M. K. Goldenblatt
H. L. Wegley
A. H. Miller
Pacific Northwest Laboratory

Objective: To examine how wind speed sampling frequency, wind turbine performance model, and wind speed forecasting accuracy affect wind-turbine economic analyses.

Discussion: JBF Scientific Corporation studied the integration of WTG into the Los Angeles Department of Water and Power (LADWP) generating system. The study used a time-dependent model supplied by Pacific Northwest Laboratory, and static models and utility production cost models supplied by JBF.

The initial phase of the study consisted of calculating the expected output of the Boeing MOD-2 wind turbine using four turbine performance models driven by wind data of different sampling frequencies. The basic wind data set consisted of instantaneous values of wind speed and direction recorded at two-minute intervals, taken at the U.S. Department of Energy meteorological tower in San Geronio Pass, California. The hourly MOD-2 outputs defined by the four models were used as load modification input to define the net load on the LADWP conventional generating sources. The net loads calculated for the 1995

LADWP generating system assumed a WTG penetration of ten percent of the anticipated peak load.

The second phase of the study consisted of examining the impact that wind forecasting accuracy would have on LADWP operation and costs.

Seventeen figures and 11 tables are included. Four appendices treat supporting technical information.

Conclusions: Modeling WTG output with a time-dependent simulation and using two-minute data appreciably change the MOD-2 capacity factor, production cost savings, and life-cycle savings from those calculated using any of the three static performance models. The ability of LADWP to forecast wind speeds accurately may increase the production cost savings by nearly twenty percent annually, and may decrease its dependence on oil-fired generation.

Caution must be exercised when generalizing the results of this study, since they were obtained by analyzing a single utility under specific assumptions.

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Analytical Studies and Field Measurements of Infrasound Propagation at Howard's Knob, North Carolina

A Subcontract Report for Solar Energy
Research Institute

D. W. Thomson
Pennsylvania State University
Department of Meteorology
University Park, Pennsylvania

Objective: To document the results of both a computational and field measurement effort to assess the physical parameters responsible for propagating infrasound near the MOD-1 Wind Turbine installation near Howard's Knob, North Carolina.

Discussion: In the study, wind and temperature profiles that could be used to model sound propagation at the site were synthesized. Two sound direction and ranging systems were operated near the site for about

three months. The infrasound propagation was modeled using ray tracing techniques.

Eighteen figures and two tables are included.

Conclusions: The results indicate that atmospheric refraction caused by vertical wind shears is primarily responsible for the noise levels. Also, surface and ground propagation are negligible in comparison with refractive airborne propagation.

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A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications

S. J. Miley

**Department of Aerospace Engineering
Texas A&M University**

Contracted by:

Rocky Flats Wind Energy Research Center

Objective: To identify and compile a catalog of all available airfoil data that is applicable to the Reynolds number operating range of small wind energy conversion systems (SWECS).

Discussion: Developers of SWECS which utilize conventional airfoil shapes depend upon the availability of low Reynolds number airfoil data for design and performance analyses. The available low Reynolds number data have been widely scattered, and were relatively difficult to locate, collect and verify. A literature survey was performed to acquire airfoil data at low Reynolds numbers, which would be applicable to SWECS. The data were screened and the most reliable were cataloged.

Twenty-four figures and three tables are included and a list of symbols is given. Three appendices present the airfoil data, an index, and a list of the information sources used in the survey.

Conclusions: These data, the most current and valid, available, are given both in tabular and graphical form. Each entry includes airfoil coordinates, lift, drag, and pitching moment characteristics. To assist the SWECS developer, an elementary discussion is given concerning airfoil behavior and the effects of Reynolds number, surface roughness, and turbulence.

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Dynamic Stall of Small Wind Systems

R. B. Noll
N. D. Ham
Aerospace Systems, Inc.

Contracted by:
Rocky Flats Wind Energy Research Center

Objective: To describe a study of dynamic stall of small wind systems.

Discussion: Aerospace Systems, Inc. (ASI) conducted a study of small wind system dynamic stall to define its influence on the airfoil force and moment coefficients. These effects can then be included in the calculation of small wind energy conversion system (SWECS) loads and responses. The study included a review of previous work to determine its applicability to SWECS, a definition of a dynamic stall theory for use in SWECS design, and computer implementation of the theory in SWECS loads and dynamic response analyses. Sample calculations are presented for representative horizontal-axis (HAWT) and vertical-axis (VAWT) wind turbines.

A table of nomenclature explains the abbreviations and special terms used in the report. Supporting technical information and a listing of the computer code are included in the four appendices. A bibliography lists dynamic stall and related technology literature chronologically by year. Nine tables and 33 figures are included.

Conclusions: The results for a fixed-pitch HAWT show that dynamic stall effects may increase normal loads and moments by about ten percent. For the cyclic-pitch VAWT, the peak normal load may be slightly underestimated, but the peak moment may be significantly underestimated. The consequences of dynamic stall may be a change in performance with a resultant mismatch of selected components or a reduction in the fatigue life of the SWECS structure.

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Solar Report Summary

Issued January 1985

Environmental Noise Levels at the DOE MOD-2 Wind Turbine Located at Goodnoe Hills, Washington

Solar Energy Research Institute

Objective: To document the methods and results of the acoustic survey of background noise at the Bonneville Power Administration Wind Turbine Site at Goodnoe Hills, Washington before installation and subsequent operation of the cluster of three DOE/NASA MOD-2 wind turbines.

Discussion: Researchers measured infrasound and audible noise levels at the BPA meteorological tower and two additional field sites from 17 June to 20 June 1980. Measurements were designed to establish background noise levels between 0.1 and 20,000 Hz. The equipment used for this survey consisted of standard acoustic survey equipment and specialized low-frequency microphone systems. The report lists in detail what equipment was used at each site. Data were analyzed using a Community Noise Analyzer

probabilistic analysis and spectrum analysis of both acoustic and infrasound levels.

Nineteen figures and two tables are included.

Conclusions: Findings indicated that the Goodnoe Hills site is acoustically typical of little-developed rural areas and that there were no major sources of man-made noise at the wind turbine site other than those associated with the wind turbine construction. Besides providing useful acoustic baseline data, the survey demonstrated that further improvements in measurement techniques could be made. Among the suggestions listed are surveying of sites at several different times during the year and the use of portable, battery-operated, covered instruments at unattended locations.

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Issued January 1985

Finite Element Analysis and Modal Testing of a Rotating Wind Turbine

Thomas G. Carne
Donald W. Lobitz
Arlo R. Nord
Robert A. Watson
Sandia National Laboratories

Objective: To describe predictive and experimental techniques for identifying the modal characteristics of a vertical axis wind turbine (VAWT).

Discussion: A finite element analysis procedure, which includes geometric stiffening effects, and centrifugal and Coriolis terms due to the use of a rotating coordinate system, has been developed to compute the mode shapes and frequencies of rotating structures. This approach has been applied to Darrieus VAWTs. Additionally, a technique for modal testing of

a rotating VAWT has been developed. The results of the predictive and experimental techniques are compared in this paper for a wide range of rotational speeds.

Seventeen figures are included.

Conclusions: The accuracy of the finite element technique for computing VAWT modal characteristics has been verified. The experimental modal testing technique for VAWT's can be used to determine the modal characteristics of existing hardware.

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Issued January 1985

Flow Visualization Study of the MOD-2 Wind Turbine Wake

H. T. Liu
Flow Industries, Inc.

Contracted by:
Pacific Northwest Laboratory

Objective: To characterize large turbine wakes under a range of atmospheric conditions.

Discussion: Flow visualization experiments were conducted in the wake of a MOD-2 wind turbine at the Goodnoe Hills Wind Turbine Site near Goldendale, Washington. The wake characteristics studied were the wake geometry, the vertical profiles of longitudinal velocity and velocity deficit, and the rotor tip vortices. Such information is needed to determine design criteria for optimum turbine spacing and configuration of wind farms. Several tracer methods were used in the experiments, such as point and line sources of smoke tracers, balloons, and flow streamers, to make visible the flow phenomena under study. The visual results were recorded on still and movie film for analysis. Turbine number 3 at the Goodnoe Hills site was used exclusively for the experiments. The experiments consisted of five on-site measurement periods, and were divided into two phases. During the first phase,

preliminary tests were conducted to develop several optimal methods for investigating of specific flow phenomena. During the second phase, the flow visualization experiments were performed using techniques resulting from the preliminary tests.

In the final report, a discussion of wind turbine wakes is followed by a description of the experimental procedures and the results.

Two tables and 38 figures are included. Three appendices contain supporting technical information, including the computer code used for analysis.

Conclusions: Comparison of the experimental results with a simple model shows a tendency for the model to overpredict wake growth and to underpredict velocity deficit. Further research is recommended to verify and refine the analysis so that it can be used effectively in developing wind turbine spacing criteria and to maximize turbine array performance.

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Issued January 1985

Guy Cable Design and Damping for Vertical Axis Wind Turbines

Thomas G. Carne
Sandia National Laboratories

Objective: To examine various principles of wind tower guy cable design, and present a technique for damping cable vibrations.

Discussion: Guys must be designed to provide both the required strength and the required stiffness at the top of the tower. However, the weight of the guy cables applies an undesirable axial load on the tower, its bearings, and its foundation; limiting this axial load so that it does not significantly affect the cost of the tower is an important objective of the cable design. These aspects of cable design are discussed in this report, along with a novel technique for damping cable vibrations.

The damping technique uses Coulomb friction to dissipate the resonant energy of the cable. A pair of weights is suspended from the cable so that they slide on two inclined surfaces whenever the cable moves. The surfaces are at right angles to each other and at right angles to the cable, so that they can damp the motion of any lateral cable vibration.

Fourteen figures complement the text.

Conclusions: The guy cable damping technique demonstrated appears to work well in reducing resonant vibration of the cables.

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Solar Report Summary

Issued January 1985

Methods for Analysis of Wind Ripple in Wind Turbines

R. E. Akins
Sandia National Laboratories

Objective: Present data reduction techniques that may be applied to analyze the wind ripple of a wind turbine.

Discussion: The output of a wind turbine may fluctuate due to variations in the incident wind; it also may fluctuate in a steady wind, due to the aerodynamics of the wind turbine. The first fluctuation is called wind ripple, while the second is called torque, or power ripple. In analyzing the performance of a wind turbine, it is important to be able to discriminate between these two effects.

As a part of the U.S. Department of Energy (DOE) Vertical-Axis-Wind-Turbine (VAWT) program, four data-reduction techniques have been developed to analyze the wind ripple of a wind turbine. The four techniques are: extension of the method of bins, a data reduction technique for full-scale performance analysis of wind turbines developed at Sandia Laboratories; a spectral density concept; long-time averages; and a transfer function between the input velocity and turbine out-

put. These techniques are discussed in this report, and examples of their application are presented using actual data records from the DOE/Sandia seventeen-meter VAWT.

Three figures and eight tables are included. The appendix contains listings of the relevant computer programs.

Conclusions: The bins approach has two disadvantages: the need to select an averaging period for the calculation of standard deviations, and the lack of output information concerning the frequency content of the fluctuations. The long-time average provides a single average of the standard deviation of turbine output, which is easy to compute, but of limited value in understanding performance. The spectral density method isolates the contribution to the variance due to a specific frequency range, but it does not determine effects due to tip-speed-ratio or due to wind speed variation. Sufficient data were not available to determine properly the value of the transfer function approach.

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MOD-2 Wind Turbine Development

Larry H. Gordon
Nasa Lewis Research Center

John S. Andrews
Donald K. Zimmerman
Boeing Engineering and Construction Company

Objective: To review the development of the MOD-2 wind turbine.

Discussion: The MOD-2 turbine was developed to achieve a cost of energy for the one hundredth unit in production that will be competitive with conventional electric power generation. The MOD-2 wind turbine system background, project flow, and a chronology of events and problems leading to acceptance of the MOD-2 are addressed in the report. The role of the participating utility, the Bonneville Power Administration, is reviewed for site preparation, turbine erection and testing, remote operation, and routine operation

and maintenance. The technical areas discussed are system performance, loads, and controls. The proposed role of the Goodnoe Hills Cluster research Test Facility in research and technical development of multimegawatt turbines is also considered.

Five tables and 14 figures are included.

Conclusions: The design, fabrication, assembly, and synchronization of the three MOD-2 turbines at Goodnoe Hills represent a major advance in the development of large horizontal-axis wind turbines.

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Operational Results for the Experimental DOE/NASA MOD-0A Wind Turbine Project

R. K. Shaltens
A. G. Birchenough
NASA Lewis Research Center

Objective: To discuss the machine configuration and the advantages and disadvantages of the MOD-0A wind turbine system.

Discussion: The objective of the MOD-0A wind turbine project was to gain early experience in the operation of large wind turbines in a utility environment. Four of the experimental 200 kilowatt horizontal axis wind turbines, designed by the NASA Lewis Research Center, were built and installed at utility sites. The experimental machines were operated from November 1977 through June 1982. During this period, the machines accumulated 38,092 hours of operation

and generated 3,677 megawatts-hours of electricity. The data and experience gained from this operation are reviewed.

Nine tables and 15 figures are included.

Conclusions: The first experimental MOD-0A wind turbines have been valuable in assisting the technical development of advanced wind machines that have the potential of generating electricity at competitive cost. The MOD-0A machines have also been valuable in assessing utility compatibility and public reaction to large wind turbines.

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Issued January 1985

Oscillating Wind Energy Conversion Systems

Peter South
Richard Mitchell
Solar Energy Research Institute

Objective: Compare the aerodynamic and economic characteristics of several oscillating wind energy conversion systems (WECS).

Discussion: Three basic types of oscillating-element WECS have been proposed. The first type, the oscillating-cable WECS, is made up of a set of cables stretched between two anchor points. The "galloping" tendency of a cable is enhanced by various aerodynamic shapes, and power is extracted from the motion of the cable. The second type uses an active element that is cantilevered at the base. The third type uses a wing that moves in a direction normal to the wind. This motion is constrained by some form of track, and power is extracted from the wing.

Since the active elements of an oscillating WECS move quite differently from those of more traditional WECS, the parameters used to describe the operating characteristics, such as efficiency, must be carefully defined. This report considers the energetics of oscillating WECS, and discusses several possible parameters to be used for characterizing these systems.

Conclusions: While not yet economically competitive with more traditional WECS, the oscillating WECS systems may someday become practical alternatives for wind energy conversion.

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Issued January 1985

Spectra Over Complex Terrain in the Surface Layer

H. A. Panofsky
J. A. Dutton
David Larko
Robert Lipschitz
Gregory Stone
Pennsylvania State University

Contracted by:
Pacific Northwest Laboratory

Objective: To examine the physics and methodology of determining wind velocity spectra over complex terrain at heights comparable to that of a wind turbine tower.

Discussion: This report concentrates on wind velocity spectra and other velocity statistics over three types of complex terrain: on tops of hills or escarpments; on land, a short distance downwind from a body of water; and over rolling farmland. Of these, the first two are of special interest to wind energy conversion system engineers.

To put the complex terrain information in perspective, Section II summarizes the most important characteristics of turbulence models over uniform terrain. Section III discusses theoretical aspects of spectral char-

acteristics over complex terrain, and the following sections consider observations over complex terrain. Finally, a theory is presented to calculate the response of wind energy conversion systems to wind velocity fluctuations.

Three tables and 53 figures are included.

Conclusions: The effect of the shape of velocity spectra must be known to determine when the use of turbulence models is appropriate. Spectral shapes must be modeled accurately. Accurate and efficient methods that do not depend on traditional approximation must be developed to calculate response statistics.

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Issued January 1985

Theoretical and Experimental Power from Horizontal-Axis Wind Turbines

Larry A. Viterna
David C. Janetzke
NASA Lewis Research Center

Objective: To develop a method for calculating the output power from large horizontal-axis wind turbines.

Discussion: The method presented is based on blade element-momentum theory with empirical modifications to the airfoil data and momentum theory. Smooth airfoil data were used for the unstalled operating region. Post-stall airfoil characteristics were derived to improve correlation with measured data. Following

a brief introduction, airfoil theory is reviewed, and the theoretical airfoil calculations are compared to field measurements.

Sixteen figures and two tables are included.

Conclusions: The calculated results were in good agreement with measured data from horizontal-axis wind turbines.

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Solar Report Summary

Issued June 1986

Estimating Long-Term Mean Winds from Short-Term Wind Data

W. R. Barchet
W. E. Davis

Objective: Present research performed to examine different methods of estimating the long-term average wind speed and to compare the performance of these techniques.

Discussion: The long-term mean wind speed is an important measure of the quality of a potential site for wind energy conversion. In many cases, candidate sites that appear promising for the deployment of wind turbines do not have a long period of meteorological record. Therefore, it is necessary to develop techniques to estimate the long-term average wind speed from a short period of record.

This report presents seven techniques developed to address this issue. One eigenvector, three linear, and

three weather-pattern methods are compared for measurement periods ranging from 3 to 36 months. The data base used in the study is presented, along with the results of each technique's performance.

One figure and six tables accompany the text.

Conclusions: The best technique for less than 12 months of measurement is the eigenvector method, which uses weekly mean wind speeds; however, this method is only slightly better than the linear adjusted method. When 12 or more months of data are used, the difference in errors between techniques is slight.

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Solar Report Summary

Issued June 1986

Objective: Present a summary of the development, testing, and verification of quasidynamic computer models of the MOD-0A and MOD-2 wind turbines.

Discussion: Previously calculating the energy captured by a given wind turbine at a specific site used a "static" approach: typically either hourly wind-speed averages over a year or the Probability Distribution Function (PDF) of those winds, a wind-to-power transfer function, and heuristic factors were used to account for the losses caused by normal operational constraints. An accurate estimate of the potential annual energy production at a given site is essential to meet the energy cost goals.

This report describes the computer simulation models of the DOE 200-kW MOD-0A and 2.5-kW MOD-2 wind turbines. These models predict power output and simulate the specific turbine operations based on their individual operating strategies and power curves. The report describes both models, with

Development and Verification of MOD-2 and MOD-0A Simulation Models

A. H. Miller
W. J. Formica

information on operating strategy and output. The testing and verification of each model are presented, as are the data and results obtained during research.

Thirteen tables and 26 figures are included with the text. Additionally 2 appendices, which are the complete FORTRAN listings of the MOD-0A and MOD-2 models, are presented.

Conclusions: The report demonstrates that the operating strategy models are:

- Useful tools to estimate energy capture
- Capable of emulating the operational behavior of their respective turbines
- Potential tools to optimize site-specific operating strategies
- Potentially useful tools to design future-generation wind turbines.

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Solar Report Summary

Issued June 1986

Subhourly Wind Forecasting Techniques for Wind Turbine Operations

H. L. Wegley
M. R. Kosorok
W. J. Formica

Objective: Present research conducted to assess the reliability, appropriateness, and accuracy in wind forecasting models for wind turbine operations and for making automated forecasts of subhourly wind and wind power fluctuations.

Discussion: The planned large-scale use of wind turbine generators (WTGs) by several electric utilities has focused attention on problems associated with optimal unit commitment and dispatching when stochastic power sources are on-line. Several studies (both completed and ongoing) that deal with these problems have concluded that reliable wind and wind power forecasts would be valuable to utilities that have a significant number of WTGs.

For this report, a simple persistence model, an autoregressive model, and a generalized equivalent Markov (GEM)-like model were developed and tested using spring season data from the WKY

television tower near Oklahoma City, Okla. The three models represent a pure measurement approach, a pure statistical approach, and a statistical-physical hybrid approach, respectively. The meteorological data used in the study are described. The development of the GEM model on a carefully selected, dependent data set is presented. GEM forecasts are compared with two simpler models. Forecast verification results on the independent data are discussed for all three models.

Six figures and 12 tables accompany the text.

Conclusions: The results of this exploratory study indicate that a persistence-based approach, using on-site measurements, will probably be superior in the 10-minute time frame. The GEM model appears to have the most potential in the 30-minute and longer time frames, particularly when forecasting wind-speed fluctuations.

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Issued June 1986

Objective: Present the results of research performed to examine the nature of wind shear profiles and their variability over the height of large horizontal-axis wind turbines. Provide information on wind shear relevant to the design and operation of large wind turbines.

Discussion: The conventional concept that wind speed increases with height in the lowest 150 m (492 ft) above ground level is based on time-averaged conditions. This concept leads to the use of the classical logarithmic profile and the power-law concept to extrapolate wind speeds from lower to higher heights.

A potential problem that occurs when the average profile concept is applied to the design or operation of a rotating turbine blade is that the blade does not encounter an average wind profile. Rather, the blade experiences the wind shear and fluctuations that occur during the two to four seconds needed to complete one rotation. A high percentage of the extreme shears that occur during this short time can affect the amount of fatigue experienced by the blades, as well as the quality of power produced by the turbine.

This report presents the results of an investigation of wind-shear profiles, particularly their variability over

Wind Shear for Large Wind Turbine Generators at Selected Tall Tower Sites

D. L. Elliott

the height of large horizontal axis wind turbines. Three test sites were chosen for this study: the KYTV Tower in Oklahoma, the Medicine Bow Tower in Wyoming, and the Goodnoe Hills Tower in Washington. The methodology and the data used in the analyses are described, and each site is discussed. The results of these analyses are also presented, again with separate descriptions for each site. Shear profiles at the three locations are described, focusing on summer and winter profiles and duration exceedance curves.

The publication contains 2 tables and 30 figures.

Conclusions: The major findings of this study are:

- Significant differences exist among three types of wind turbines in the distribution, duration, and fluctuation of shear profiles.
- Large differences exist among the three locations in the distribution, duration, and fluctuation of shear profiles.
- Large variations exist between winter and summer at all three locations in the distribution, duration, and fluctuation of shear profiles.
- The distribution of wind shear profiles varies dramatically between day and night at each location.

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Issued June 1986

Objective: Present the results of research into turbulent wind analyses relevant to the design and testing of the vertical axis wind turbine (VAWT).

Discussion: The effect of turbulent wind on a moving turbine blade is an important consideration for wind turbine design. The stresses on the rotating blade caused by instantaneous wind shears encountered by the blade within each revolution are more severe and more difficult to understand than previously expected. The purpose of the study presented in this report is to estimate and characterize the turbulence at a rotating VAWT blade using data collected from a line of seven anemometers located at Clayton, N.M.

This report presents a physical description of the Clayton Vertical Plane Array (VPA) and the seven anemometers used to measure the wind. The technique of VAWT simulation is described, using a sequence of wind speeds appropriately led and lagged in time to simulate the motion of the wind turbine blade. Examples of the time series of rotational and fixed-point wind speeds are given to help understand the process. The spectral density and features of the fixed-point, one-blade simulation, and two-blade simulation spectral plots are described as well. Twelve data cases, which were selected for spectral analysis, are presented; each data set belongs to one of four distinct wind regimes at Clayton. Rotationally sampled spectra and the fixed-point

Simulation of Winds As Seen by a Rotating Vertical Axis Wind Turbine Blade

R. L. George

spectra are compared among the four categories of wind. The results of this report are compared to the results of another study, which comprised a wind measurement from a rotating VAWT blade.

The report contains 4 tables and 21 figures.

Conclusions: The major conclusions of the study are as follows:

- The characteristic rotationally sampled spectrum, containing spikes at all harmonics of the blade-rotation frequency, occurs for vertical as well as horizontal axis wind turbine simulations.
- The rotationally sampled wind-speed variance caused by turbulence is a roughly linear function of wind speed for neutral and unstable wind conditions. For stable nighttime wind conditions, this relationship is probably nonlinear.
- For tangential and radial winds, the cyclic wind component, caused by the upwind and downwind motion of the (simulated) VAWT blade, creates a variance in the wind-speed spectrum that is about 100 times greater than the variance caused by wind turbulence.
- Spectra of winds measured directly from a VAWT blade show more energy at higher harmonics of the blade-rotation frequency than the wind-turbulence simulations in this report.

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Solar Report Summary

Issued December 1986

Objective: Evaluate the effectiveness of 20% and 38% chord ailerons in controlling the rotor speed on the MOD-0 wind turbine.

Discussion: The use of ailerons in large wind turbines could reduce the cost and weight of the turbine blades compared with partial- or full-pitch blades. The aileron is used to change the lift and drag coefficients, providing aerodynamic braking of a horizontal-axis wind machine.

Two aileron designs were produced for the blade tips of the MOD-0 100-kW wind machine. The 20% chord design is a NACA 23024 airfoil with a maximum deflection angle of 60°. The larger 38% chord aileron is a NACA 64 series airfoil with a maximum deflection of 90°.

Two tests were performed with each of the ailerons: (1) a rotor overspeed test following loss of load, and (2) a no-load equilibrium rotor-speed test. The overspeed test determines the maximum speed the rotor will achieve immediately after loss of load. High rotor speeds can damage the rotors and drive train. The equilibrium test is characterized by the rotor achieving a stable rotor speed with no generator load. Tests

Aileron Controls for Wind Turbine Applications

Dean R. Miller
Richard L. Putoff

were conducted on both aileron systems at the National Aeronautics and Space Administration (NASA)/Lewis test facility at Sandusky, Ohio.

The report was prepared for the Intersociety Energy Conversion Engineering Conference of August 1984 and includes eight figures.

Conclusions: The overspeed test results showed that the 38% chord aileron design provided adequate protection from overspeed while the 20% chord aileron design did not. A computer model was used to predict the performance of the ailerons over the full range of operating wind speeds for the MOD-0. The peak overspeed for the 38% chord aileron was 22.5 rpm or an increase of only 1.8 rpm above normal operating speed. In addition, after 10 s, that speed was reduced to 12 rpm because of the rapid deflection rate of the device — 20°/s. The equilibrium test showed that the 38% aileron had a substantially lower no-load equilibrium tip-speed ratio. The 38% chord aileron provided sufficient aerodynamic braking and control for the MOD-0 wind turbine.

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Solar Report Summary

Issued December 1986

Objective: Present results of performance tests taken during varying levels of precipitation on different rotor configurations, quantify the general effects of precipitation during these tests, and use these data to provide adjustments for airfoil prediction models to account for the effects of rain.

Discussion: Three distinct characteristics of rainfall were examined in relation to their effect on a moving airfoil: (1) the loss of momentum, (2) the additional weight of the airfoil, and (3) the change in surface characteristics caused by both raindrop cratering and water films. The most important of these effects is the change in the surface characteristics (roughness) of the airfoil.

The field research was conducted at the National Aeronautics and Space Administration (NASA)-Lewis Research Test Center in Sandusky, Ohio. Field tests were conducted on the MOD-0 horizontal-axis wind turbine using three different rotor configurations. The MOD-0 turbine, a 100-kW, two-bladed turbine, was run in a downwind configuration. The rotors varied for airfoil shape, Reynolds number, and surface roughness. The first rotor configuration was a 15.3-m tip-controlled rotor. The second was a 19.5-m, 20% chord aileron-controlled rotor. The third was also 19.5 m, but with a 38% chord aileron-controlled rotor. Tests were conducted on all three rotors during dry and wet periods. The tests varied in length and other conditions. Graphs present the data for the tests and show the results of 2.5-min testing intervals for each rotor configuration. The report further defines the details of the operating conditions, test measurements, and power-train corrections used in the analysis.

The estimated effects of rainfall on wind-turbine performance were analyzed for the second configura-

Effect of Precipitation on Wind Turbine Performance

Robert D. Corrigan
R. Demiglio

tion tests. Corrections were made in a conventional rotor-performance code based on the blade-element/momentum theory developed at the Wind Energy Laboratory at Wichita State University. The method used in modifying the airfoil characteristics was developed at the Dayton Research Institute. The use of these techniques provides a means of equating the change in surface characteristics to corresponding changes in the drag and lift coefficient, which are plotted as a function of angle of attack. A comparison of the estimated and experimental data for the 20% chord aileron-controlled rotor is also shown.

Sixteen figures, primarily documenting changes in the rotor power and in the drag and lift coefficients, are included.

Conclusions: Field-test data and estimations of performance for wind turbines show a substantial reduction in performance because of precipitation. Rain caused a substantial reduction in power production in all three configurations, particularly at wind speeds over 6.5 m/s. Test data show a reduction of 20% in a light rain and more than 30% in a heavy rain. Snow mixed with rain showed even greater reduction at low wind speeds. Estimated data showed greater reduction in performance with higher rainfall.

The experimental data tended to agree with field-test data for the second rotor configuration, suggesting that the technique for adjusting the drag and lift coefficients can be used to account for the effects of rain on wind-turbine rotor characteristics.

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Solar Report Summary

Issued December 1986

Effect of Vortex Generators on the Power Conversion Performance and Structural Dynamic Loads of the MOD-2 Wind Turbine

T. Sullivan

Objective: Measure the effect of vortex generators (VG) installed on the MOD-2 wind turbines at Goldendale, Washington on both power conversion performance and on dynamic loads.

Discussion: Tests were conducted with three configurations: (1) turbines with no vortex generators on the rotor blades, (2) turbines with vortex generators added on the fixed portion of the rotor (20%-70% span), and (3) turbines with vortex generators on both the fixed portion of the rotor and the pitchable tip. Vortex generators are small metal vanes attached to the rotor blades of wind turbines. The vanes energize the boundary layer by mixing higher energy air from the free stream with boundary-layer air.

The vortex generators used varied in size depending on location on the rotor. Three sizes were used, varying from 2 x 8 cm (0.8 x 3.2 in.) for the inboard portion of the rotor to 0.6 x 2.5 cm (0.25 x 1.0 in.) for the blade tip. One-hundred seven vanes were installed on each blade for the first vortex generator configuration test and an additional ninety were installed on the tip for the second test.

The power conversion performance of the wind turbines under each configuration is analyzed using 10-min averages of midpoint generator power and wind-speed measurements. For study of dynamic effects a statistical analysis was used to provide cumulative probability distributions of midpoint and

cyclic load values. For this study statistics were done on 30-min segments of wind turbine operation. From these statistics 50th percentile (median) and 99th percentile values were used to determine the effect of vortex generators on the dynamic response of the wind turbine.

Nineteen figures and four tables are presented in the report.

Conclusions: Performance test results showed that the addition of vortex generators to the MOD-2 rotor blades resulted in a significant increase in power and annual energy capture. Application of VGs to the fixed portion of the rotor reduced the wind speed at which rated power is reached from about 16 to 13.8 m/s and increased projected annual energy capture by 11%. The addition of VGs out to the rotor tip reduced rated wind speed an additional 0.5 m/s and increased projected annual energy capture an additional 9%. This increase in performance came at little cost in increased cyclic loads. No significant difference in cyclic loads was found between the two VG configurations tested. A slight increase in blade cyclic loads in below rated power winds was found after the addition of VGs. However, because the addition of VGs also results in a decrease in peak steady loading, the overall effect of adding VGs is probably to increase blade fatigue life.

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Solar Report Summary

Issued December 1986

Objective: Evaluate advanced concepts for attaching studs to laminated wood wind turbine blades.

Discussion: Laminated wood blades have been used in large wind turbines; however, the studs, or the attachment of the blade to the spool/hub assembly, has never been optimized. The studs that were used in the MOD-0A blades could be substantially improved, resulting in possible reduction in weight and cost, and increasing the lifetime of the blades. Eight different stud and epoxy designs were tested to determine their ability to withstand ultimate load and fatigue tests. Additional tests were performed to examine the effects of temperature and humidity. One of the eight stud configurations was designed to duplicate the stud design used on the MOD-0A blades and provide a baseline for comparison. The other stud configurations were designed to alter one parameter at a time to examine the effects of that parameter. These parameters were length of tip drilling, tip diameter, stud modulus, taper shape, and block modulus. Gougeon Brothers, Inc. was responsible for the overall contract. Illinois Institute of Technology (IIT) Research Institute tested the samples.

Each of the test studs was embedded in a 3-in.² wood block 24 in. long — except the MOD-0A stud, which required a 4-in.² block. Each configuration was tested

Improved Stud Configurations for Attaching Laminated Wood Wind Turbine Blades

James R. Faddoul

for static load until failure occurred. The fatigue test was conducted by subjecting the sample to minimum and maximum compression and tension loads. The tensile machine would alternate the minimum and maximum values for a fixed period in compression and then in tension. The experimental setup would not allow true compression and tension testing but instead tried to simulate the R = -1 test. The document includes 4 tables and 19 figures.

Conclusions: The testing resulted in a stud configuration that can approach the membrane strength for wood (ultimate load exceeding 100,000 lb per stud). The improved design increases the fatigue stress capability by a factor of two over the stud design used in the MOD-0A blades. The introduction of carbon-fiber filler in the epoxy improved the fatigue life over the asbestos-fiber-filled resin. When subjected to high humidity and high-temperature conditions, the performance of the stud configuration was degraded by 30%-50%. This factor requires additional testing and analysis. Other conclusions presented in the report deal with the actual design parameters such as the tip drilling, effect of stud surface area, and stud taper ratios.

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Solar Report Summary

Issued December 1986

Objective: Measure the turbulent wind with a vertical plane array of anemometers upwind of the turbine, analyze it in the rotational frame of the rotor blades, and correlate the results with turbine performance at the Clayton, New Mexico, vertical plane array (VPA)/MOD-0A project.

Discussion: The influence of turbulent wind on a moving wind-turbine blade is a significant consideration for wind-turbine design. The stresses on the rotating blade, caused by instantaneous wind shears within each revolution, are more severe and difficult to understand than previously expected. Turbulent wind was measured for a large array of fixed anemometers located two blade diameters upwind of a 200-kW horizontal-axis wind turbine. Key wind-turbine-response parameters were also measured simultaneously. The two major goals of the program are to (1) determine the turbulent wind for the range of different wind speeds and stability classes experienced by the wind turbine, and (2) correlate this rotationally sampled wind with the turbine blade stress and power, assessing the usefulness of the wind measurements for testing and predicting wind-turbine loads.

Descriptions of the vertical plane arrays, the MOD-0A wind turbine, and the Clayton site are presented, along with the wind sensors, data-collection approach, and collected data. The computer programs and techniques involved in the study and their applications are described. The criteria for the selection and analysis of 12 different data cases are discussed, with information concerning spectral density and harmonics. A com-

Rotationally Sampled Wind Characteristics and Correlations with MOD-0A Turbine Response

R. L. George
J. R. Connell

parison of MOD-0A blade-bending moment with VPA-measured winds is presented, focusing on transfer-function calculations and comparisons. Harmonic variance data are also included.

Seven tables and twenty-two figures accompany the text.

Conclusions: The major conclusions of the report are:

- The spectra of rotationally sampled wind show greatly enhanced energy at the blade-rotation frequency and higher harmonics for all winds tested.
- The amount of energy fluctuation in the rotationally sampled wind spectra resulting from mean vertical wind shear can be separated from the energy solely caused by turbulence. The mean wind shear generally is not the dominant factor; turbulence is.
- A high correlation, never previously obtained, is observed between the spectra of rotationally sampled wind speed and the spectra of blade flapwise bending moment for all cases.
- The spectra of blade flapwise bending moment show enhanced response at the known first and second flapwise resonant frequencies, previously computed from static measurements.
- The effective aerodynamic damping coefficient is estimated to be 0.35 for the first flapwise resonance frequency of the MOD-0A fiberglass blade.

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Solar Report Summary

Issued December 1986

Objective: Show both estimated and experimental results for a 38% chord aileron in terms of its ability to control rotor speed in emergency situations.

Discussion: Two basic tests were conducted to examine the applicability of the 38% aileron blade used in conjunction with the MOD-0 horizontal-axis wind turbine. (These tests were conducted at the National Aeronautics and Space Administration [NASA]/Lewis Test Center in Sandusky, Ohio.) The first test for overspeed examined the ability of the aileron system to control the rotor speed following loss of generator load. In addition to conducting experimental tests, the authors predicted the aerodynamic braking capability of this aileron-controlled rotor as a function of aileron deployment rate.

The loss-of-load overspeed tests were conducted with the wind turbine aligned into the wind and producing power. The generator load was then dropped and one or both ailerons actuated into the shutdown position. From this data, a relationship between the field tests and the experimental data was developed. Once defined, the predictive model was used to evaluate the performance under maximum wind speeds.

The second test examined the no-load equilibrium rotor speed for various fixed-aileron deflections. The

Shutdown Characteristics of the MOD-0 Wind Turbine with Aileron Controls

D. R. Miller
R. D. Corrigan

experiment was conducted with both ailerons deflected because of excessive teeter motion with only single-aileron deployment.

This report was prepared for the Horizontal-Axis Wind Turbine Technology Workshop, May 8-10, 1984. Sixteen figures and one table are included.

Conclusions: The tests on the 38% chord ailerons showed full overspeed protection for the MOD-0 wind turbine over the entire operating range for the device. The ability of the researchers to predict the performance of the turbine was very good for both one-aileron and two-aileron tests. The agreement between the field-test results and the predicted values for overspeed tests also was very good. A discrepancy of -4% and +4% was cited for the two-aileron peak rotor speed test and -8% and +4% for the one-aileron test. Under maximum wind conditions (18 m/s cutout speed), the peak overspeed was limited to 31% and 23% using one and two ailerons, respectively. The no-load equilibrium test showed that the two-aileron shutdown had twice the deceleration (1.2 rpm/s) of the single-aileron test (0.6 rpm/s).

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Solar Report Summary

Issued April 1989

Analysis and Test Results for an Improved Constant Speed Passive Cyclic Pitch Wind Turbine Final Subcontract Report

K. H. Hohenemser

Objective: Determine whether the conventional blade pitch control of wind turbines with high initial and maintenance costs can be replaced by a rotor yaw control.

Discussion: The research described in this report was conducted at the Department of Mechanical Engineering, Washington University, St. Louis, Missouri, under subcontract to the Solar Energy Research Institute, in Golden, Colorado. Modifications were made to a horizontal wind turbine with a two-bladed, passive cyclic pitch (PCP) rotor, 25 ft (7.6 m) in diameter.

The primary modification involved removing the boom pin, which was previously located downwind of the yaw axis and served to attach the boom to the nacelle. In the modified design, the boom is supported by the yaw post and moves together with the post. The nacelle, previously bolted to the yaw post, is now capable of rotating 90° about the yaw post with the help of two ball bearings. Thus, tail boom yawing and nacelle furling are now independent functions, causing little friction.

Additional modifications were found necessary to increase performance: the blade airfoil was extended toward the rotor center with a high twist, which greatly

improved start-up; the shaft-mounted gearbox with a belt-driven generator was replaced by an integral gear-generator unit, which reduced the break-out torque by 80%; and some erratic yawing at low wind speed power-on was corrected by increasing the tail vane area and lengthening the tail boom.

The report contains with 28 figures and six tables of data.

Conclusions: Although the modifications made to the PCP wind turbine improved the power-on operation in severe turbulence, it is still less than desirable because of furl and power fluctuation with the natural tail vane period measured to be several seconds. This period should be lengthened by aerodynamic or mechanical means. The modifications were made on a trial-and-error basis and analysis was hampered by the lack of an analytical yaw control dynamics model. Once such a model is available, a generic study of torque and speed control by yawing of teeter rotors should be undertaken. It appears that the PCP rotor continued to function well up to high yaw rates and high wind velocities, but problems encountered by the combination of a passive furl control system and a fast reacting wind-following tail vane could not be corrected.

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Applications & Commercialization

General Solar Topics

Hybrid/Total Energy Systems

13 Hybrid/Total Energy
Systems

SERI Report Summary

Conversion System Overview Assessment, Volume II— Solar-Wind Hybrid Systems

T. S. Jayadev
J. Henderson
C. Bingham

Objective: Present an assessment of solar-wind hybrid systems for energy conversion applications.

Discussion: Using solar and wind data from ten different sites in the United States, the complementarity of solar and wind energy resources is discussed. The sites used are: Bismark, N.D.; Dodge City, Kan.; Albuquerque, N.M.; Santa Maria, Calif.; Lake Charles, La.; Madison, Wis.; El Paso, Texas; Fort Worth, Texas; Boston, Mass.; and Seattle, Wash. For each site, power availability from each source, the complementarity of power from the two

sources, and estimated power output from model generation systems were considered. Additionally, a computer simulation was performed to demonstrate the potential of solar-wind hybrid systems for industrial applications.

Conclusions: There are large areas in the United States where solar and wind resources are comparable in magnitude, and there are diurnal and seasonal complementarities which offer potential for cost-effective solar-wind hybrid systems.

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SERI Report Summary

Conversion System Overview Assessment, Volume III— Solar Thermal/Coal or Biomass Derived Fuels

R. J. Copeland

Objective: Present an assessment of the potential for production of synthetic fuels using solar thermal heat.

Discussion: This report presents the results of a study that evaluated the cost of producing synthetic fuel using solar thermal heat combined with coal or biomass. Using normal insolation data for the United States, projected costs for coal and biomass, and anticipated costs for solar thermal

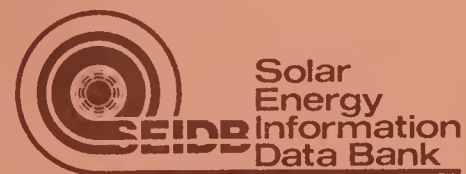
energy, the costs of producing methane are considered.

Conclusions: Given the projected costs of coal, biomass, and solar thermal energy, synthetic fuels produced using solar thermal energy will be cost-competitive with the same fuels produced using coal or biomass, if either the future costs of coal or biomass are near the high end of present projections, or the cost of solar thermal energy can be reduced below current estimates.

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Solar Report Summary

Issued November 1982

Review of Thermally Regenerative Electro- chemical Systems

Helena L. Chum
Robert A. Osteryoung

Objective: Review and classify past and present work on thermally regenerative electrochemical systems.

Discussion: Thermally regenerative electrochemical systems (TRES) are closed systems that convert heat into electricity in an electrochemical heat engine that is Carnot cycle limited in efficiency. Two broad classes of TRES can be identified by the type of energy input required to regenerate the electrochemical cell reactants: thermal input only (discussed in sections I and II) or the coupling of thermal and electrolytic energy inputs (discussed in sections III through V). These two broad categories are further divided into seven types of TRES (types 1-3 for thermal regeneration; types 4-7 for coupled thermal and electrolytic regeneration), according to significant differences in either the electrochemical cells or in the regenerators. Each type of TRES is defined and discussed in detail in the report.

Volume I is an executive summary of the full report, which comprises Volume II. Volumes I and II are structured identically. Volume I contains seven figures and nine tables. Volume II contains 57 figures and 24 tables. A reference list of 228 publications is included in Volume I.

Conclusions:

- Systems operating at lower temperatures should be investigated.
- The search for possible new types of TRES should be continued.
- Areas recommended for long-range benefit to TRES technology include molten salt chemistry and electrochemistry, solid-state chemistry, materials sciences, aqueous systems and electrochemistry under extreme conditions, electrochemical engineering, and systems analysis.

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Solar Report Summary

Issued June 1986

Objective: Present the results of research on vapor-phase, heat-transport systems that are being tested in two of the passive cells at the Los Alamos National Laboratory (LANL).

Discussion: Vapor-transport systems can improve performance over current active and passive solar energy space-heating systems because higher heat transfer rates are obtained in the evaporation and condensation process and lower heat losses occur at night. LANL is investigating a system consisting of an active-type solar collector with passive water storage. The passive discharge operates at lower temperatures, which improves performance.

A computer model was developed to predict the behavior of a system consisting of an active fin-and-tube collector and a condenser inside a water storage tank. Then the computer predicted the annual performance of these systems in five cities (Albuquerque,

Performance of an Active/Passive Hybrid Solar System Utilizing Vapor Transport

James C. Hedstrom

que, N.M.; Madison, Wis.; Washington, D.C.; Phoenix, Ariz.; and Denver, Colo.). This report compares the measured and predicted results, as well as the system's sensitivity to several parameters.

A detailed description of the experiment is presented. The results are discussed and the computer model and its functions are described. The validation results are also presented, along with a comparison between calculated and measured results. A sensitivity study and its results are described as well.

The report contains 7 tables and 21 figures.

Conclusions: The computer program and model are adequate to provide a realistic annual performance estimate of an actual vapor-transport system for several climates.

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Materials Research

Information Systems

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Materials Research

17 Materials Research

Materials Research

SERI Report Summary

SERI Materials Branch Semiannual Report January 1, 1978 - June 30, 1978

Materials Branch Staff
Dr. Barry L. Butler, Chief

Objective: Provide information on the status of materials research activities at the Solar Energy Research Institute.

Discussion: The Materials Branch has used its resources, which include 14 people, to meet the commitments of the Annual Operating Plan (AOP) for FY78. Comprehensive planning, laboratory development, and cooperative research programs with subcontractors are reported. Initial planning has provided direction for materials research at SERI. Program planning activities have been consolidated so that the plans for reflector, absorber, and polymer materials research are complementary to each other and support the Branch effort to assess materials limitations in solar energy conversion systems. The planning for a laboratory to carry out solar materials research is being guided by both the long-range programs mentioned above and by the programs proposed in the AOP for FY79 which was sent to the Department of Energy (DOE).

Equipment ordered and laboratory layouts are described in the report. Cooperative research arrangements with Clarkson College and with the Colorado School of Mines are discussed. Negotiations for contracts to survey the properties of new

thermoelectric materials, to study more corrosion resistant silver alloys for second-surface plastic mirrors, and to study the ultraviolet degradation of selected polymers are reviewed for the reader.

Four tables and four figures are included.

Conclusions: During FY78, the following subcontracted research programs were initiated:

- silver alloy coating for polymer supported reflectors,
- black chrome and black cobalt selective absorbers,
- corrosion monitoring methods and equipment development,
- sorption by desiccant,
- solar thermoelectric conversion,
- ultraviolet degradation of polymeric materials, and
- reliability and standards.

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Materials Branch personnel provided assistance to DOE in technical monitoring and consultation in workshops and in planning for standards guidelines. Technical monitoring support of ongoing DOE contracts in the absorber materials activity within the Advanced Solar Thermal Technology Branch was provided. SERI assisted DOE in establishing optical measurement standards, performance specifications, and process guidelines during FY78.

Materials Branch personnel presented numerous talks on solar energy and served on various international and national committees of professional importance during FY78.

Significant progress was made toward establishment of materials laboratory facilities during FY78.

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SERI Report Summary

Reliability and Durability Study of a Thermal Receiver Utilizing ASI Type 316 Stainless Steel in Contact With Molten Aluminum

John D. Webb
Steven L. Pohlman

Objective: Present the results of a study of the compatibility of ASI Type 316 stainless steel with molten aluminum.

Discussion: Probable lifetimes are determined for unprotected components exposed to the liquid aluminum used to transfer and store heat in a solar receiver supplied to SERI by the Omnium-G Company. This receiver was tested on the manufacturer's Heliodyne point-focusing solar concentrator installed at the SERI field testing site. The receiver failed quickly, resulting in the leakage of a small amount of molten aluminum.

Samples of the stainless steel used in the receiver were laboratory tested to determine why and how quickly it was affected by the molten aluminum.

The report is complemented by 11 figures and four detailed tables of data and results. Appendices A and B contain sample data and calculations. Appendix C is a glossary of terms used in the report.

Conclusions:

- The Omnium-G receiver is not safe to operate

above the melting point of the aluminum heat transfer medium.

- Analysis of the aluminum that leaked from the receiver during field testing showed that some dissolution of the steel components had occurred during the brief tests.
- The rate of dissolution of the steel components is highly dependent on temperature.
- The pitting model developed in the study enables good correlation of laboratory data collected on the initial dissolution rate of Type 316 stainless steel.
- The pitting model indicates that mean pit depth increases in direct proportion to exposure time, regardless of the number of attack sites present.
- Inconel 600 alloy dissolved uniformly in molten aluminum, with formation of a relatively thick, high-melting attack product at the liquid-solid interface.

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SERI Report Summary

Use of a Fabry-Perot Resonator at Millimeter Wave Frequencies in the Determination of Thin Film Resistivities

Stephen J. Hogan

Objective: Develop a contact-free method of measuring resistivity of thin semiconductor films on highly conductive substrates.

Discussion: This report discusses in detail the microwave technique for measuring resistivity of thin semiconducting films on highly conductive substrates that uses a semiconfocal Fabry-Perot cavity at a wavelength of 3 mm. The sample is a thin film of cadmium sulfide on a brass substrate and is mounted on the flat reflector of the cavity. Using field perturbation methods, an expression is

derived that relates the film resistivity to the cavity quality factor Q . Accuracy of measurements and necessary sample constraints are discussed in detail.

Sixteen figures and five tables are included.

Conclusions: The new technique provides a nondestructive way of measuring the resistivity of semiconductor films on conducting substrates and is suitable for automation.

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SERI Report Summary

Design for a Gas Chromatograph for Characterizing Desiccant Material

R. Pitts
A. Czanderna

Objective: Summarize the design criteria for a vapor phase chromatographic sorption apparatus for testing desiccant materials used in solar air conditioning.

Discussion: One method that has been proposed for solar air conditioning involves the use of desiccants. Air is passed through a desiccant bed for drying, then brought to thermal equilibrium with the surrounding air, and finally reloaded with water vapor to provide air conditioning.

The water vapor adsorption-desorption processes by desiccant materials need to be measured. One measurement technique uses gas chromatography. This report examines the design for such a chromatograph.

After a discussion of the applicability of gas chromatography to sorption measurements, the detailed design is presented.

Four figures and one table accompany the text. Appendix A is a shopping list of major equipment needed for the measurements, while Appendix B explains some important aspects of desiccant geometry.

Conclusions: Gas chromatography may be used to advantage in sorption studies since the measurement column can be constructed to closely simulate the configuration in which the desiccant will actually be used. On the other hand, some materials may have a difficult geometry to simulate. Although the chromatographic technique does suffer this and other minor limitations, it should prove to be a valuable tool for measuring desiccant properties.

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SERI Report Summary

MIS and SIS Solar Cells on Polycrystalline Silicon

Gary Cheek
Robert Mertens

Objective: Review the status of Metal-Insulator-Semiconductor (MIS) and Semiconductor-Insulator-Semiconductor (SIS) solar cell technology and assess the potential of this technology to meet low cost goals.

Discussion: Three major types of MIS/SIS solar cells are discussed in terms of structure, materials used in the fabrication, and the current collection under illumination. The types of solar cells discussed include the thin metal MIS structure, the conducting oxide SIS structure, and the MIS inversion layer device. The specific advantages of MIS and SIS solar cells are investigated using theoretical calculations. The spectral response, short-circuit current, open-circuit voltage, fill factor, and cell efficiency are presented for MIS and SIS solar cells, as well as for advanced diffused and standard diffused solar cells.

Six figures and three tables accompany the report text.

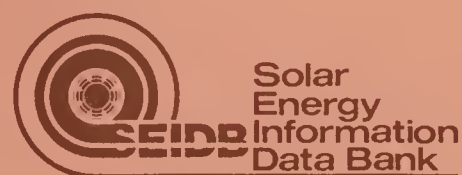
Conclusions: A major conclusion of this report is that MIS and SIS solar cells have no real advantages over solar cells using diffused p-n junctions. Potential advantages of the MIS/SIS technology include a better response to blue light than diffused cells and the use of a low-temperature fabrication processes.

In general, MIS/SIS fabrication techniques are more complex than those for diffused cells. Thus, conversion to MIS/SIS technology is not cost-effective unless nonvacuum processes are used. Although the theoretical efficiency of MIS and SIS solar cells is higher than diffused cell efficiencies, actual measured efficiencies are considerably lower. Therefore, MIS/SIS technology will be economically competitive only after significant increases in actual operating efficiency.

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SERI Report Summary

National Program Plan for Absorber Surfaces R&D

Patrick J. Call

Objective: Describe a National Plan for Absorber Surfaces Research and Development (R&D).

Discussion: The objective of the Absorber Surface R&D program is the timely development of high performance, durable, and cost-effective solar absorbers for use in solar thermal systems through a cooperative government, industry, and university effort. The program plan is projected for five years with maximum industrial involvement in the development projects. Universities and national laboratories will be used primarily for research and support activities. The program will lower front-end risks by providing research funds to demonstrate technical feasibility of absorber surface concepts. Cost-sharing assistance in the development stage will provide further support. Commercial markets will be stimulated by identifying applications, certifying test procedures, and providing information.

This report describes four absorber surface development activities in detail: improved selective absorbers to 200°C, black chrome to 400°C, selective absorbers to 700°C, and absorber surfaces (optical and protective properties) above 700°C. Support activities for the program include optical measurements, durability testing, component evaluation, systems

analysis, data base management, and basic research.

Twenty figures and eight tables complement the text.

Conclusions:

- A number of high-priority R&D topics, as listed in the report, should be pursued to assure the success of the National Plan for Absorber Surfaces R&D.
- Measured optical properties of absorber surfaces will be required for engineering design, hardware verification and control, durability test analysis, and coating development.
- The systems analysis activity initiated by the Jet Propulsion Laboratory (JPL) should be refined and extended through a joint SERI/JPL effort.
- The data base activity will be a part of a larger SERI priority program—the Solar Energy Information Data Base.
- Basic research will emphasize the understanding of degradation mechanisms and absorber modeling.

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SERI Report Summary

Polymers in Solar Technologies: An R&D Strategy

William F. Carroll
Paul Schissel

Objective: Present a five-year research and development (R&D) program to investigate the potential impact of polymers on solar technology.

Discussion: The report outlines an R&D program organized around six problem areas:

- a material's interaction with the environment,
- photodegradation,
- permeability and adhesion,
- surfaces and interfaces,
- thermomechanical behavior, and
- new materials and processes.

The tasks related to each problem area are discussed in detail, and resource requirements for each task are outlined.

One figure and five tables complement the text.

Conclusions: Polymers have many potential applications in solar technologies that can help achieve total system cost-effectiveness. To realize that potential, three major parameters must be optimized: cost, performance, and durability. The five-year R&D program outlined in this report will contribute toward those optimizations.

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Solar Report Summary

Issued November 1982

Evaluation of Thick-Film Inks for Solar Cell Grid Metallization

Steve Hogan
Kay Firor

Objective: Present research findings on the performance characteristics of commercially available metallization pastes.

Discussion: A number of ink manufacturers sell thick-film compositions for general metallization, and many have modified their inks especially for contacting solar cells. Manufacturers were first surveyed to determine which inks were commercially available for applying to the front (grid) surface of single-crystal silicon cells. These inks were then obtained and processed to determine their performance characteristics when fired onto solar cells. Performance characteristics examined included current-voltage curves, contact and series resistance values, adhesion properties, and ability to withstand a brief environmental exposure test. Other ink properties, such as afterprint flow and ease of cleaning, also were noted.

Several ink manufacturers recommended non-noble metal-based inks in addition to the commonly used silver inks. These inks were also examined for potential applications and were compared with silver inks.

Fifteen figures and one table are included. Four appendices present details of the correspondence with ink manufacturers and of the measurements.

Conclusions: Most of the twelve silver inks examined yielded good results. Many inks required optimized processing. All inks required etching in hydrofluoric acid to achieve maximum electrical performance. Both the glass content and amount of dopant materials in the inks were found to be important parameters. None of the non-noble metal-based inks gave satisfactory results. The silver-bearing inks are cost-effective and perform acceptably when applied to solar cells designed for terrestrial use.

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Solar Report Summary

Issued November 1982

Physical, Chemical, and Electrical Studies of Silicon MIS Solar Cells

Martin A. Green

Objective: Investigate the physical, chemical, and electrical properties of high-performance, MIS (metal/insulator/semiconductor) based silicon solar cells.

Discussion: The distinctive feature of an MIS cell is the metal/insulator/semiconductor heterojunction structure. The insulator layer, normally a thermal oxide, is sufficiently thin that a current can flow through it by quantum mechanical tunneling processes.

High-resolution electron microscopy (HREM) was used to image the ultra-thin oxides used in the MIS cells. The images were then used to study the physical structure of the materials. The chemical composition of the ultra-thin oxides was investigated using x-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES). The electrical properties of the cells were determined for varying temperature.

The HREM studies indicated that the oxide was of uniform thickness, with no evidence of large pinholes

or metallic inclusions. It appeared to be an interfacial layer of comparable quality to the substantially thicker oxides used in microelectronics. Initial work with both XPS and AES indicated the presence of silicon dioxide. Subsequent experiments with AES failed to detect this oxide. This casts doubt on the initial experiments.

Ten figures and three tables are included.

Conclusions: MINP (Metal-Insulator-N P Junction) solar cells incorporating the MIS structure displayed creditable efficiencies and exceptionally high open-circuit voltages. A theoretical consequence of these high voltages is a reduced temperature coefficient of efficiency. Experimental measurements of the coefficients of MINP cells confirmed substantially lower temperature sensitivity than conventional silicon cells, the measured sensitivity being approximately halfway between that of normal silicon cells and gallium arsenide cells.

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Solar Report Summary

Issued November 1982

Silicon Dendritic Web Material Process Development

D. L. Meier
R. B. Campbell
L. J. Sienkiewicz
P. Rai-Choudhury

Objective: Develop a low-cost contact system for solar cells and integrate techniques for fabricating, interconnecting, and encapsulating solar cells to produce demonstration modules.

Discussion: Two experimental contact systems were examined and compared to a baseline contact system consisting of evaporated layers of titanium, palladium, and silver and an electroplated layer of copper. The first experimental system consisted of evaporated layers of titanium, nickel, and copper, and an electroplated copper layer. The second experimental contact system consisted of evaporated layers of nickel and copper and an electroplated layer of copper. Auger electron spectroscopy was used to show that the evaporated nickel layer is not an adequate barrier to copper diffusion at temperatures as low as 250°C (482°F). Three modules were fabricated using cells made from dendritic web silicon. Ultrasonic seam

bonding was used to interconnect the cells into strings, and ethylene vinyl acetate was used to encapsulate these cell strings. The first two modules were of nominal 30 by 60-centimeter size and the third module was of nominal 36 by 118-centimeter size.

Twenty-one figures and eleven tables are included. An appendix presents process specifications for module fabrication.

Conclusions: The first experimental system performed as well as the baseline system in all respects. However, the second system, in addition to the inadequacy of the evaporated nickel layer, was afflicted with adherence problems between the silicon and the evaporated nickel. It is not viewed as a promising contact system. The efficiency of the third fabricated module was 10.6 percent in natural sunlight.

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Solar Report Summary

Issued September 1983

Tunnel Diode Interconnect Junctions for Cascade Solar Cells

R. E. Hayes
M. Kowalchik
P. Gibart
S. Wagner
J. Chevrier

Objective: Study tunnel diodes grown by liquid phase epitaxy (LPE) in gallium arsenide (GaAs) and higher-bandgap ternary compounds for use as interconnect junctions in multijunction cascade solar cells.

Discussion: Since a cascade cell is operated under high sunlight concentrations, the tunnel junction must be stable with time at a peak current of 25 amperes per square centimeter. No serious degradation should occur during the growth of the wide bandgap top cell. The work reported had two goals. One was to determine whether degradation could be minimized by using germanium (Ge) and tellurium (Te), which have smaller diffusion coefficients than the more commonly used zinc (Zn) and tin (Sn), as doping elements. The other goal was to investigate the nature of the degradation process itself. The extra highly doped hole/electron GaAs tunnel junctions

were grown by LPE in a conventional sliding-boat apparatus and were subjected to anneals ranging up to 24 hours. Diodes were prepared, and the current-voltage characteristics were measured.

Seven figures are included.

Conclusions: The peak tunneling current degraded significantly at growth temperature as a result of anneal times at the growth temperature as short as 30 minutes. The peak current degradation due to high-temperature annealing of the positive (Ge-doped) to negative (Te-doped) LPE junctions is attributed to impurity diffusion. For typical doping densities, the product of the impurity diffusion coefficient and the high-temperature processing time must be less than 10^{-12} square centimeters to avoid severe tunnel current degradation.

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Solar Report Summary

Issued January 1985

Examination, Evaluation, and Repair of Laminated Wood Blades after Service on the MOD-0A Wind Turbine

James R. Faddoul
NASA Lewis Research Center

Objective: To pursue the development of low cost rotor blade technology for large, horizontal-axis wind turbines (HAWT).

Discussion: Two sets of wood blades were returned for inspection after service on MOD-0A wind turbines. One set had been in Hawaii for 17 months (7,844 hours of operation), and the other had been at Block Island, Rhode Island, for 26 months (7,564 hours of operation). The Hawaii set was returned because one of the studs that hold the blade to the turbine hub had failed. This was caused by a combination of improper installation and inadequate corrosion protection. No other problems were found. The Block Island blades were returned at the completion of the MOD-0A test program. One blade was found to have developed a

crack in the leading edge along the entire span. This crack was the result of a manufacturing process problem, but was not structurally critical.

One table and 29 figures are included.

Conclusions: In general, the laminate quality of both sets of blades tested was excellent. No significant lamination or structural defects were found in any blades. The stud bonding process requires close tolerance control and adequate corrosion protection, but studs can be removed and replaced without major problems. Moisture content stabilization does not appear to be a problem, and laminated wood blades are satisfactory for long-term operation on MOD-0A wind turbines.

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Solar Report Summary

Issued January 1985

An Experimental Approach to Evaluating Environmental Degradation Mechanisms in Bisphenol-A Polycarbonate Films on Metallic Substrates

John D. Webb

Solar Energy Research Institute

Objective: To demonstrate the applicability of an experimental approach to the study of photodegradation of polymer films on metal surfaces.

Discussion: Bisphenol-A polycarbonate (BPA-PC) polymer was chosen since its bulk photochemistry has been studied extensively, enabling the results of earlier studies to be compared to those obtained using the new experimental method. Knowledge of the outdoor stability of polymer films on metallic surfaces is important in the design of solar energy collection devices such as heliostats and photovoltaic cells.

The technique described in this report uses a controlled environmental exposure chamber in conjunction with a Fourier transform infrared spectrophotometer to enable study of degradation reaction mechanisms of polymer/metal samples exposed to simulated outdoor conditions. The chamber design permits collection of infrared reflection-absorbance (IR-RA) spectra from a polymer film (on a reflective metal) undergoing exposure to controlled ultraviolet (UV) radiation, gas mixtures, and temperatures. Changes in the IR-RA spectrum of a sample can be related to changes in the molecular structure of the polymer film and chemical changes at the polymer/metal interface.

A technique for relating the IR-RA band heights measured with the apparatus to the concentration of polymeric functional groups and reaction products in the

coatings is presented. Two methods for obtaining this information, involving polarimetry or an absorbance measurement of the k spectrum followed by Kramers-Kronig (KK) prediction of the n spectrum, are presented and compared. These data lead to the recommendation of an optimum range of polymer film thicknesses, 0.1-1.0 μm , for the study of changes in the important functional groups of BPA-PC on good IR reflectors. Most of the samples in this study were thicker than this, but much useful information was obtained. For example, an optical model enabled the concentrations of reaction products in BPA-PC/gold samples exposed under different conditions to be plotted as a function of exposure time.

Forty-three figures and eleven tables are included.

Conclusions:

1. The in-situ method of IR-RA spectroscopic analysis of the photodegradation of polymer/metal samples, when used in conjunction with UV spectroscopy and gel permeation chromatography (GPC) was successful in making a detailed qualitative assessment of reaction mechanisms. The major mechanisms observed, in order of importance, were the first and second photo-Fries rearrangements of carbonyl then chain scission. These reactions have been cited for BPA-PC by other researchers. Evidence for reactions not previously reported, including accumulation of adsorbed carbon dioxide in the polymer films and

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photooxidation of the BPA-PC methyl groups, was also obtained. Chain scission and adsorbed carbon dioxide will reduce the rigidity of BPA-PC.

2. The FTIR-RA method was also demonstrated to yield accurate quantitative mechanistic data. Measurements of the bulk concentration of the product of (first) photo-Fries rearrangement made using IR-RA spectroscopy were demonstrated to be accurate, using UV-RA spectroscopy as a check. Quantum yields of polymer photoproducts calculated using the IR-RA concentration measurements were comparable with those obtained by other researchers. Accumulation of these photoproducts will reduce the solar transmittance of BPA-PC.

3. The observation of linearity of photoproduct accumulation in the thinnest films studied indicates that the photo-Fries rearrangement products are ineffective in screening high UV fluxes in thin BPA-PC films and are also not effective as quenchers. For these reasons, salicylate or benzophenone stabilizers are predicted to be ineffective in preventing surface photodegradation of BPA-PC. Stability of polymer surfaces in solar collection devices is important if properties such as dust rejection, specularity, and impact resistance are to be retained.

4. The techniques presented should be applicable to the study of both bulk and interfacial degradation of polymer films on any reflecting substrate. For the study of bulk BPA-PC polymer photodegradation, samples should have thicknesses between 0.1 and 1.0 μm , where 100 FTIR scans of such samples will

provide adequate signal to noise ratios. The thicknesses and number of scans best suited for the study of any polymer can be deduced from the methods developed for BPA-PC. For the study of interfacial degradation, thinner polymer films and a greater number of FTIR scans may be employed. The IR-RA method is also applicable for weathering studies of polymer surfaces; optimization of the number of scans was not considered.

5. Operation of the prototype Controlled Environmental Exposure Chamber (CEEC) at the University of Denver (DU) suggested significant improvements in the subsequent design of the SERI unit. Data from both units were utilized.

6. A successful technique for measuring the infrared complex refractive indices of sheet polymers was developed and employed. The data resulting from determining these indices for BPA-PC enabled other quantitative results to be obtained for this polymer.

7. Pronounced ablation (reduction in thickness) was noted for several exposed samples. The implication is that some of the photoproducts are volatile at room temperature.

8. The UV output spectra of the solar simulators of SERI and DU were measured, enabling calculation of quantum yields for some of the photoreactions. The agreement of the measured quantum yields with literature values is an indication of the accuracy of the UV spectroradiometric procedures employed, as well as of the IR-RA technique of concentration measurement.

Solar Report Summary

Issued January 1985

Fabrication of Low-Cost MOD-0A Wood Composite Wind Turbine Blades

R. F. Lark
M. Gougeon
G. Thomas
M. Zuteck
NASA Lewis Research Center

Objective: To briefly describe the design and analysis, and review in depth the fabrication of low-cost wood composite turbine blades for the MOD-0A system.

Discussion: Wood composite blades were fabricated for the MOD-0A wind turbine system, using epoxy resin-bonded laminates of Douglas fir veneers for the leading edge spar sections, and honeycomb-cored birch plywood panels for the blade trailing edge or afterbody sections. The blade was joined to the wind turbine hub assembly by epoxy resin-bonded steel studs. The wood composite blades were installed in

the newest MOD-0A wind turbine test facility at Kahuku, Hawaii. The blades successfully completed eighteen months service before removal for replacement with another set of blades.

Two tables and 59 figures are included.

Conclusions: The wood composite MOD-0A blade design and fabrication process described in this report can provide low cost blades. The wood composite construction was still intact after eighteen months service on the MOD-0A system.

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Solar Report Summary

Issued January 1985

Los Alamos Optical Materials Reliability, Maintainability, and Exposure Testing Program

S. W. Moore
Los Alamos National Laboratory

Objective: To document the investigations performed by Los Alamos National Laboratory under the United States Department of Energy Active Heating and Cooling Materials Reliability, Maintainability, and Exposure Testing Program.

Discussion: The major limitations to the use of solar energy are the uncertain reliability and lifetimes of solar systems. This program is aimed at determining material operating limitations, durabilities, and failure modes such that materials can be improved, and lifetimes can be extended. The work reviewed in this

report addresses three primary areas: exposure testing of materials, collector site materials evaluations, and long-term collector materials durability study. Collector materials and components from a number of sites and collector types were studied in each of these areas.

Ten figures and 12 tables are included.

Conclusions: Reliability and lifetimes of the different materials and components studied varied significantly. Technical details are included in the report.

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Solar Report Summary

Issued June 1986

Objective: Describe a multiprogram, modular software system for analyzing laboratory data on a medium-sized computer.

Discussion: This report describes the computer environment for projects that involve research and testing of building materials and components. Phase-change-materials (PCM) research and calorimetric performance measurements in building research are used to illustrate the functional capabilities and operational procedure of the modular acquisition and display software (MADS) system.

MADS, which consists of computer programming modules, allows the researcher to design an experimental process by selecting relevant modules. The researcher can acquire, validate, graphically analyze, and store data. MADS also enables the instrumentation staff to monitor and manage data for several research projects that operate concurrently on a single computing system.

This report presents telecommunication methods, laboratory instrumentation, the operating system, utilities, and applications software. The modular

Modular Data Acquisition and Display Software System for a Laboratory Environment

Lawrence Kaetzel
John Grimes
Paul Brown

acquisition and display system, especially the eight MADS software modules, is described. These modules involve various monitoring, acquisition, data-prepping, report-generating, and graphics-generating programs. A discussion of data-base storage is included, as are sections on operator references, program enhancements, and file security.

The 14 appendices display several format and plot examples, as well as sample file listings. The report has 3 tables and 10 figures.¹

Conclusions: Using the MADS system can increase research productivity for the following reasons:

- The computer staff can monitor computer system utility, and the researcher can devote more time to laboratory research.
- Compressed file formats allow rapid and efficient data analyses.
- Additional research projects can be added to the system with a minimal amount of computer program coding.

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Solar Report Summary

Issued December 1986

Objective: Present the results of exposure testing on absorber coatings and the degradation of these coatings.

Discussion: Los Alamos National Laboratory (LANL), under the auspices of the U.S. Department of Energy's (DOE) Active Heating and Cooling Materials Reliability, Maintainability, and Exposure Testing Program, has developed a computer modeling program to determine potential performance benefits of various solar materials. This report concentrates on absorber coatings and their degradation.

The selective absorber coatings evaluated by LANL are nickel-pigmented anodic Al_2O_3 on aluminum, Cr-CrO₂ composite film on aluminum, colored stainless steel, chemical conversion coatings on copper and brass, chemical conversion coatings on nickel, chemical conversion coatings on zinc or zinc/aluminum, chemical conversion coatings on stainless steel, SnO₂ coating on porcelain enamel, thickness-sensitive selective paints, and thickness-insensitive selective paints. These coatings had not reached full commercialization in the United States when they were selected for evaluation. Test results for two full-sized collector-absorber types, black chrome and black nickel, are presented.

Absorber Coatings' Degradation

S. W. Moore

Four tables, elucidating test results, and two figures accompany the text. This report was presented at the 1984 RETSIE (Renewable Energy Technologies Symposium and International Exposition) Conference in Anaheim, California.

Conclusions: Three major research results are detailed in this report:

- Results on coatings vary from no change in optical properties to decreases in performance for 3-month, 6-month, and 12-month exposure testing for coating.
- Black-chrome selective absorbers show only insignificant change after five years of stagnation testing.
- Tests of samples taken from the Miromit collector used on a housing project in Denver, Colorado indicate significant visual color changes with little difference among the integrated absorptances over a 2-year period.

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Solar Report Summary

Issued April 1989

DTA/DSC Studies of Phase Equilibria in Binary Mixtures of Barium Carbonate with Alkali Carbonates

R. E. Mills
R. T. Coyle

Objective: Describe the study of binary mixtures of BaCO_3 with Li_2CO_3 , Na_2CO_3 , or K_2CO_3 to gain information helpful in determining if BaCO_3 might be useful as a partial replacement for Li_2CO_3 in the ternary mixture of the alkali carbonates used as a heat storage and heat-transfer medium in some central solar receivers.

Discussion: Phase relations for mixtures of BaCO_3 with three alkali carbonates were studied using the Perkin-Elmer DTA 1700 instrument operated in the DSC (differential scanning calorimeters) mode, with all samples in a CO_2 atmosphere. The Tammann Rule on latent heat was significant in locating invariant points and boundaries of first-order transitions.

For the mixtures $(\text{Li}_2\text{CO}_3)_{1-x}(\text{BaCO}_3)_x$, a eutectic transition was observed at $640 \pm 3^\circ\text{C}$ for x in the interval (2.55, 96.4) mol% with $x_{\text{eu}} = 39.4$ mol%. A solid solution is indicated for $x > 96.4$ mol%. Polymorphic transitions were observed at $807 \pm 1^\circ\text{C}$ for $x > 53$ mol% and at $966 \pm 1^\circ\text{C}$ for $x > 64$ mol%.

The mixtures $(\text{Na}_2\text{CO}_3)_{1-x}(\text{BaCO}_3)_x$ showed a solid solution region for $x < 5$ mol% and a eutectic transition at $702 \pm 2^\circ\text{C}$ for $x > 5$ mol% with $x_{\text{eu}} = 34.6$ mol%. Polymorphic transitions were observed at $805 \pm 1^\circ\text{C}$ for $x > 50$ mol% and at $965 \pm 2^\circ\text{C}$ for $x > 60$ mol%. The presence of a very narrow range of high temperature solid solutions is inferred for x near 100 mol%.

The mixtures $(\text{K}_2\text{CO}_3)_{1-x}(\text{BaCO}_3)_x$ have a solid solution region for $x < 25$ mol%, and a eutectic transition that extends from 25 mol% to 80 mol% with $x_{\text{eu}} = 44.0$ mol%. The eutectic line terminates at a coordinated compound $\text{K}_2\text{Ba}_4(\text{CO}_3)_5$, which melts incongruently at $899 \pm 3^\circ\text{C}$. The incongruent melting occurs for x in the interval (58, 100) mol%. Polymorphic transitions occur at $808 \pm 1^\circ\text{C}$ for $x > 80$ mol% and at $970 \pm 1^\circ\text{C}$ for $x > 60$ mol%. The presence of a very narrow range of high temperature solid solutions is inferred for x near 100 mol%. For low x , the melting temperature increases from $897 \pm 1^\circ\text{C}$ for pure K_2CO_3 to $917 \pm 1^\circ\text{C}$ for $x = 6$ mol% before beginning the normal decrease in liquidus for increasing x .

This report contains 13 figures and four tables.

Conclusions: This study of binary mixtures was a necessary first step toward gaining information about quaternary mixtures of these salts. The experimental technique (differential thermal analysis) compared the thermal features of mixtures of neighboring concentrations and provided a reliable way of identifying the nature of the phenomena displayed by the apparatus as various peaks. Supplementary information about the liquidus features of K_2CO_3 - BaCO_3 is needed, especially at higher BaCO_3 concentrations. Using x-rays to further study the anomalous melting of the mixtures at low BaCO_3 concentrations and of the coordinated compound $\text{K}_2\text{Ba}_4(\text{CO}_3)_5$ would be desirable.

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Models & Simulations

SERI Report Summary

Application of Monte Carlo Techniques to Insolation Characterization and Prediction: Status Report October 1, 1978-June 1979

Richard Bird
Roland Hulstrom

Objective: Describe preliminary research in the use of Monte Carlo techniques for studying various aspects of solar radiation transport.

Discussion: This report presents the preliminary results of a study using the Monte Carlo method to investigate solar radiation transport through the atmosphere and its reflection from the earth's surface. The rigorous model used in the study allows a detailed understanding of the various aspects of the radiation field at the earth's surface. This knowledge can be used to compare and formulate simple models appropriate to solar applications. This report is preliminary in that it is primarily a description of the Monte Carlo method and its applications, rather than a detailed presentation of results. Phenomena discussed in the report include:

- spectral distribution of direct, diffuse-sky, and ground-reflected insolation;

- total broad band insolation;
- circumsolar insolation;
- effects of ground albedo;
- relationships between insolation on horizontal surfaces and on tilted surfaces;
- the importance of higher orders of scattering and reflection;
- effects of clouds; and
- effects of various types of atmospheric aerosols.

Conclusions: In the future, output from the Monte Carlo codes will be compared with a variety of carefully compiled insolation data. These data will be collected at the Insolation Research Laboratory near the Solar Energy Research Institute in Golden, Colo.

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SERI Report Summary

Simulations and Economic Analysis of Desiccant Cooling Systems

Benjamin C. Shelpuk
Douglas W. Hooker
Gary J. Jorgensen
Carl E. Bingham

Objective: Document progress to date in the development of computer simulations and analysis of solar-powered desiccant cooling using an axial-flow, disc-type dehumidifier wheel; solar-powered space heating; and electrically driven, standard vapor-compression air-conditioning systems for residential use.

Discussion: Computer simulations for both solar and conventional heating and cooling systems were performed for 12-month heating and cooling seasons. Annual thermal performance and the resulting life cycle costs for both types of systems were analyzed and compared.

Heating/cooling season simulations were conducted for five U.S. cities representing a wide range of climatic conditions and insolation. Using information obtained from these simulations, the optimum air-conditioning system was chosen to maximize the conservation of fossil fuels and minimize operating costs. Due to increasing use of residential air conditioning employing electrically driven, vapor-compression coolers, the five locations were studied to determine if it would be beneficial (in terms of both economics and fossil fuel displacement) to replace fossil-fuel-powered, vapor-compression coolers and natural gas space

heaters with solar-powered heating and desiccant cooling systems.

The text is supplemented with 27 tables, 68 figures, and four appendices.

Conclusions:

- Solar heating and desiccant cooling systems operate best in climates with nearly balanced heating and cooling loads.
- Solar desiccant coolers operate preferentially as dehumidifiers.
- The optimum desiccant cooler size for a home in Washington, D.C., with auxiliary cooling, and a home in Dodge City, Kan., without auxiliary cooling, is 4.5 kW with a 35 m² collector area.
- The life-cycle cost of a 20-year solar heating/desiccant cooling system is nearly cost competitive with conventional residential heating and cooling systems.
- Adding a desiccant cooler (with or without auxiliary cooling) to a solar heating system can double energy output, depending on the location.

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SERI Report Summary

Insolation Models, Data and Algorithms Annual Report FY78

Roland L. Hulstrom

Objective: Describe the research tasks of the SERI Insolation Models, Data and Algorithms Program.

Discussion: The objectives, descriptions, and results of insolation research tasks of SERI's Energy Resource Assessment Branch (ERAB) are presented for FY78. The purpose of ERAB is to provide state-of-the-art and advanced state-of-the-art data bases and physical models to ensure accurate design and analyses of solar energy conversion device performance. The tasks performed during FY78, the first year of operation for SERI/ERAB, addressed the resources of insolation and wind. The insolation portion of FY78 work is described. That work resulted in operational computer models for the thermal (broadband) and spectral insolation, a data base (SOLMET) for the U.S. geographical distribution of thermal insolation, preliminary research measurements of the thermal insolation on tilted surfaces, and a complete design concept of advanced instrumentation to measure automatically the insolation on 37 tilted surfaces at various orientations.

The text is complemented by 31 figures.

Conclusions: The major SERI/ERAB FY78 effort consisted of:

- Obtaining measurements of insolation on tilted surfaces.
- Reviewing, comparing, and evaluating algorithms for converting horizontal insolation to tilted surfaces.
- Designing and developing an Insolation Research Facility (IRF).
- Providing broadband and spectral insolation models to other SERI investigators and branches.
- Assisting the Department of Energy (DOE) in developing solar energy training sites at universities.
- Obtaining and implementing the SOLMET data base and the Standard Meteorological Year tapes.
- Assisting the private sector with insolation models and data bases.

Significant progress was made during the first year of operation of SERI/ERAB, and continued operation will help ensure rapid progress in the area of insolation models, data, and algorithms.

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SERI Report Summary

Direct Insolation Models

Richard Bird
Roland L. Hulstrom

Objective: Compare several simple, direct insolation models with a rigorous solar transmission model and describe an improved, simple, direct insolation model.

Discussion: This study compares several of the more recent direct insolation models for clear sky conditions. The comparison includes seven simple models and one rigorous model that is a basis for determining accuracy. The results of the comparisons are then used to formulate two simple models of differing complexity. The most useful aspects of present models have been incorporated into the new models.

The criteria used for evaluating and formulating models in this report are simplicity, accuracy, and the ability to use readily available meteorological data.

The ultimate goal of the work reported here is the production of a well-documented global insolation model that includes the direct and diffuse clear sky insolation as well as cloud- and ground-reflected insolation.

Thirteen figures, seven tables and one appendix are part of this report.

Conclusions: The recently developed, rigorous, spectral radiation transport model (SOLTRAN) was modified to give the capability of calculating the broad band (thermal solar energy) direct solar beam irradiance. This modified version of SOLTRAN can be utilized to generate the intensity

of the direct solar beam versus time of day for various locations and atmospheric conditions. Such information is crucial to the design and performance analyses of solar concentrator systems.

The broad band SOLTRAN was used to delineate the relative importance of the various atmospheric constituents in the transmittance of direct beam solar energy. Aerosols appear to dominate the attenuation under most conditions, molecular scattering is next in importance, and water vapor absorption is third. Attenuation caused by CO_2 , O_2 and O_3 is minor.

The two simple models that were formulated as a result of this study provide results that are in excellent agreement with SOLTRAN results, and these models are very easy to use.

The absolute accuracy of SOLTRAN and the simple models can be determined only by comparisons

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with actual measurements of the direct solar beam irradiance and measurements of the atmospheric inputs.

Insolation and meteorological data to be collected by the SERI Resource Assessment Branch and the

Solar Energy Meteorological Research and Training sites will greatly advance the state of knowledge concerning the atmospheric influences on the direct solar beam irradiance and will lead to improved designs for solar energy conversion devices.

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SERI Report Summary

A Review of Regional Economic Models With Special Reference to Labor Impact Assessment

Gregg Ferris
Bert Mason

Objective: Review regional economic models and examine their capabilities for assessing total employment impacts of solar energy adoption.

Discussion: Five generic analytic methods are discussed:

- economic base analysis,
- shift-share analysis,
- demographic-economic interaction models,
- input-output analysis, and
- industrial location analysis.

Ten regional models incorporating some aspect of these methods are reviewed.

Conclusions: There is no single model that fits all of the necessary criteria for planned research efforts. Models that hold promise are:

- Economic Activity Analysis (EAA),
- Regional Industrial Multipliers (RIMS),
- Multiregion, Multi industry (MRMI), and
- MULTIREGION.

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SERI Report Summary

A Sensitivity Analysis of SPURR

Robert E. Witholder

Objective: Describe the results of sensitivity analysis of SPURR (System for Projecting the Utilization of Renewable Resources, developed by the MITRE Corporation).

Discussion: Sensitivity analysis was performed on the agricultural and industrial process heat and utility market sectors of the SPURR model to determine if variations in solar system capital cost, operational and maintenance cost, and fuel cost correlate with 'common sense' and agree with intuition.

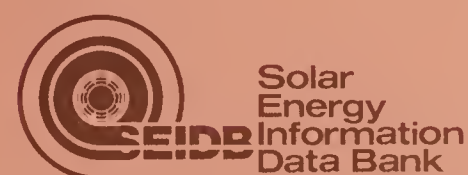
Variations of the above factors were evaluated for the following output parameters: accumulated installed systems, annual energy production, accumulated capital cost, and accumulated life-cycle cost.

Conclusions: Further research efforts on SPURR will be conducted after a coding problem in the output report of the SHACOB (solar heating and cooling of buildings) component is corrected. Meanwhile, SPURR must be modified so that variations in system lifetime can be included.

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SERI Report Summary

The Potential Displacement of Petroleum Imports by Solar Energy Technologies

Peter deLeon
Byron L. Jackson
Robert F. McNown
Gary J. Mahrenholz

Objective: Analyze the economic, social, and political costs of U.S. dependence on foreign oil.

Discussion: According to this report, recent analyses of the U.S. energy crisis show that while a declared policy goal is reduced reliance upon imported petroleum, the nation is becoming more and more dependent upon it. Two aspects of this contradiction are presented. First, the cost of our dependence on foreign petroleum is examined. Second, the question of how this cost can be reduced is discussed. The report specifically examines the capabilities of solar energy technologies to reduce our current use of petroleum as an energy resource and to reduce the amount of petroleum imported.

A computer model developed by the MITRE Corporation, SPURR (System for Projecting Utilization of Renewable Resources), was used for estimating the amount of oil that might be displaced by solar technologies by the year 2000. The SPURR model compares the probable range of costs for both conventional and solar technologies in four energy markets: heating and cooling of residential and commercial buildings, agricultural

and industrial process heat, generation of electricity by the utility sector, and the synthetic fuels market. Market penetration curves govern the rate of new technology introduction. The results of analysis of each primary energy market by geographic region is a projected mix of conventional, solar, and synthetic fuel technologies to meet new demands for energy.

Two appendices explain the methodology of the SPURR model and the background of the National Energy Plan.

Four figures and four tables complement the text.

Conclusions:

- Solar energy will displace 0.65 quad per year, or 320,000 barrels per day, of petroleum as an energy resource.
- Solar technologies will also displace large amounts of coal and nuclear energy in domestic consumption, possibly as much as 3.0 quads by the year 2000.
- Three quads of oil per year could be displaced in the transportation sector by gasohol.

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SERI Report Summary

Evaluation of the "Typical Meteorological Years" for the Solar Heating and Cooling System Studies Final Report

Thomas L. Freeman

Objective: Evaluate the "Typical Meteorological Year" (TMY) data set generated by Sandia Laboratories and determine how well the TMY data represent actual long-term weather data in affecting the performance of solar heating and cooling (SHAC) systems.

Discussion: One of the obstacles to SHAC studies has been the lack of a commonly accepted year of hourly meteorological data for use in computer simulations. Consequently it has been very difficult to compare the performance of different component and system designs as simulated by different investigators. To address this problem, the Department of Energy (DOE) contracted for Sandia Laboratories to generate the TMY data for

each of 26 U.S. cities that have a long period of recorded hourly meteorological data.

In this study, SHAC computer simulations are used to compare the TMY and actual data sets.

Conclusions: The main value of the TMYs to most researchers is that they offer standardized hourly meteorological forcing functions for a wide variety of climates. If more TMY data are to be generated, the following modifications should be considered: hourly values of the data inputs should be biased so that their monthly averages agree with those for the long term, and a means should be devised to represent spring and fall months within the data structure.

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SERI Report Summary

End-Use Matching for Solar Industrial Process Heat: Final Report

Kenneth C. Brown
Douglas W. Hooker
Ari Rabl
Shirley A. Stadjuhar
Ronald E. West

Objective: Provide an applications analysis, through an end-use matching approach, for solar industrial process heat in six U.S. cities, determine the most promising industries for the near-term application of solar process heat technology, and identify the most appropriate equipment and systems now available for solar process heat.

Discussion: Four data bases are described: the Industrial Process Heat Data Base (IPHDB), a catalog of process characteristics by SIC code; the Collector Equipment Data Base; a Meteorological Data Base; and an Economic Factors Data Base. The simulation model PROSYS (Process System Simulation), which was developed for use in assessing the performance of various solar industrial process heat systems, is outlined. In order to rank the matches of collector, system, process, and location tested; the life-cycle costs of a solar industrial process heat system are calculated by a companion code called ECONMAT (Economic Matching Model). The economic end-use matching analysis evaluates technically feasible system/process/location combinations and provides an economic ranking. The results of two case studies of the potential

industrial application of solar energy are discussed.

Seven appendices are included which give the details of the data base contents, the methodology for collector performance evaluation, a detailed description of the economic matching routine, and technical observations associated with the case studies.

Thirty-three figures and 40 tables supplement the text.

Conclusions:

- The IPHDB should be modified to include sufficient details on processes so that an end-use matching analysis does not impose unnecessarily restrictive requirements on solar system modeling.
- Since PROSYS is very useful in case study analyses, the capabilities of the model should be expanded.
- Future case studies should concentrate on those industries that are most promising for solar applications.

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Models & Simulations

SERI Report Summary

Issued June 1981

A TRNSYS-Compatible Standardized Load Model for Residential System Studies Final Report

P.J. Hughes
J.H. Morehouse

Objective: Present a standard load model for use in residential forced-air heating, ventilation, and cooling system analysis.

Discussion: This report discusses a computerized energy load model which is compatible with the TRNSYS (Transient System) computer analysis code and which is designed for temperature level control analysis. Model parameters are defined for three representative locations: Fort Worth, Texas, Washington, D.C., and Madison, Wis. For each location, a typical conventional residence is specified using the load model parameters.

The load model is described in detail and a FORTRAN listing of the model code is included. An example problem is presented to illustrate the use of the model.

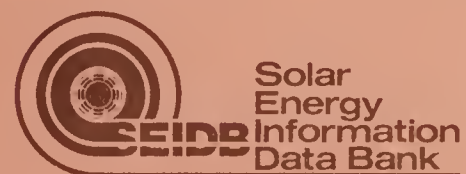
Five tables and 14 figures accompany the text.

Conclusions: The standard load model provides a means to compare heating and cooling systems while interfaced with an identical load forcing function.

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SERI Report Summary

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Investigation of Simple Daily Solar Radiation Models Suitable for Use in the Design of Solar Heating Systems

Sanford Sillman

Objective: Investigate the feasibility of using daily weather data to simulate the annual performance of solar heating systems.

Discussion: Solar heating system simulations typically require the use of hourly weather data. While such models are highly accurate, they require use of a main-frame computer, and up to 10,000 data inputs per computer run. An alternative approach is to use a sinusoidal model for daily solar radiation, and to base the performance simulation on daily, rather than on hourly, data. Such a simulation would require only 1,460 data inputs and could be run on a microcomputer.

In this report, a theoretical comparison is made between daily radiation model results and hourly data for each day of the year in 10 U. S. cities. Additionally, the accuracy of daily radiation data is assessed.

Eight figures complement the text.

Conclusions: The use of daily weather data with a radiation model is accurate enough to be used in place of hourly weather data to simulate the performance of active solar heating systems. Daily total and maximum insolation data should be collected for use in such radiation models.

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SERI Report Summary

Issued June 1981

Open-Cycle OTEC System Performance Analysis

A. A. Lewandowski
D. A. Olson
D. H. Johnson

Objective: Describe an algorithm which calculates the performance of Claudecycle ocean thermal energy conversion (OTEC) systems.

Discussion: A Claude-cycle OTEC plant consists of an evaporator, a vapor turbine, a cold water pipe, warm and cold water pumps, a condenser exhaust pump, and sometimes warm and cold water aerators. The subject algorithm treats each system component separately and then interfaces them to form the system, so that each component can be modified without changing the rest of the algorithm.

Models were developed for different system configurations, and the algorithm was used to calculate the performance effect of deaerating the warm and cold water streams before they enter the

evaporator and condenser of an open-cycle OTEC system, respectively.

Two tables and 34 figures are included in the report. A printout of the algorithm is presented as an appendix.

Conclusion: The study of deaeration indicates that there is no advantage to removing air from the warm and cold water streams before they enter the evaporator and condenser of an open-cycle OTEC system, respectively. Assumptions made in developing the algorithm preclude its use to analyze the actual performance of a particular system. These assumptions also cause inefficiency preferentially to influence cost rather than performance.

Efforts should continue to improve this performance-analysis algorithm.

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Issued June 1981

Mist Lift Analysis Summary Report

Roger L. Davenport

Objective: Study the mist lift process and its use in Ocean Thermal Energy Conversion (OTEC).

Discussion: The major component of a mist flow OTEC plant is the mist lift tube, which converts the thermal energy of surface sea water into gravitational potential energy that can be transformed into useful energy by a hydraulic turbine. Water is lifted against gravity by vertically flowing a mist of water droplets and lower-pressure water vapor inside the lift tube. The mist is generated by injecting fine, superheated water drops into the bottom of the tube. Some of the drops evaporate, and the resulting vapor expands toward the top of the tube, carrying the unevaporated water drops along by viscous drag. At the top, cold water from deep in the ocean is used to condense the vapor, and the liquid drops are collected.

This report summarizes the progress made at SERI

in the study of the mist lift process during fiscal year (FY) 1979 and early FY 1980. During that time, models were developed of a single-drop-size mist and a mist composed of many drop sizes. Results from both models and directions for further work are discussed.

Nine figures and four tables accompany the text.

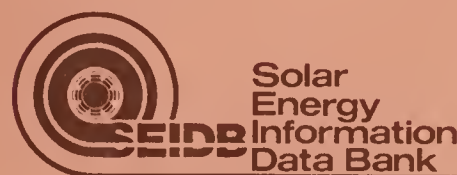
Conclusions: The single-drop-size model predicts that the range of inlet pressure/flow rate combinations under which the mist flow will operate is rather narrow. The multiple-drop-size model indicates that the growth of droplets by collision and coalescence is significant. Due to this growth, the height possible for mist flow is much lower than that predicted by the single-drop-size model.

Future work will emphasize better understanding of the collisions of drops in lowpressure vapor, improvement of the model codes, and injector-design alternatives.

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Summary of Currently Used Wind Turbine Performance Prediction Computer Codes

Fred Perkins

Objective: Present a compendium of existing wind power system simulation models.

Discussion: Summary information is presented for each of 17 wind power system simulation models. For each model, the included information is:

- name of code,
- originator,
- reference source,
- input requirements,
- output data,
- description of code,
- availability, and
- contact person.

The 17 codes represent the response from 25 organizations originally contacted. All the contractors identified in the Summary of the Federal

Wind Energy Program (DOE/ET-0023/1) that had contracts with Rocky Flats, SERI, or NASA Lewis Research Center were contacted, as well as Sandia Laboratories, JBF Scientific, and NASA Lewis. No independent manufacturers or investigators were contacted.

One table is included in the report.

Conclusions: While many codes have been written for horizontal axis wind turbines, theoretical development has lagged behind for vertical axis machines. For example, only one model was reported for aerodynamic performance of a Darrieus machine.

In the reported economic models, little concern is shown for the effect of load feedback on the predicted performance, or for the effects of the control system and transient parameters on the instantaneous power output.

A code should be developed that can resolve the aerodynamic input to a wind system, model the load, and implement the control system for optimum energy production.

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A Comparison of DOE-2 and TRNSYS Solar Heating System Simulation

Anthony Eden
Marion Morgan

Objective: Compare the output from the two solar heating system simulation models, DOE-2 Component Based Simulator (CBS) and TRNSYS (Transient System Simulation Program).

Discussion: The output of the two codes was compared for interfacing of various active solar collectors with a standard space heating system. The codes were run for both single- and double-glazed windows with selectively and nonselectively coated absorbing surfaces located in four different environments.

Twenty-four figures and four tables are included. Three appendices present listings of the two codes and sample output data.

Conclusions: The two models agree remarkably well. A number of suggested modifications are mentioned in the report, but both of the models are valuable in solar heating system design and evaluation.

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Issued November 1982

Active Charge/Passive Discharge Solar Heating Systems: Thermal Analysis and Performance Comparisons

Joel Swisher

Objective: Develop a simple thermal analysis method for active charge/passive discharge solar space-heating systems and make cost/performance comparisons with other solar designs.

Discussion: The performance of active charge/passive discharge solar space-heating systems is analyzed. This type of hybrid system combines liquid-cooled solar panels with a massive integral storage component that passively heats the building interior by radiation and free convection.

The Transient System (TRNSYS) simulation program is used to evaluate system performance and to provide inputs for the development of a simple analysis method. This method, which produces monthly calculations of delivered solar energy, is based on Klein's Phi-bar procedure, using data from hourly TRNSYS simulations. Correlations are developed to estimate monthly average collector temperature as a function of absorbed solar radiation, building load, storage capacity, and storage-to-room conductance. In the Phi-bar technique, this temperature is used, along with other system parameters and radiation data, to determine the usable fraction of the absorbed radiation. The method also accounts for energy dumped to prevent overheating and for energy lost to the ground where a floor slab is used for the storage component.

The method can be applied to systems using a floor slab, a structural wall, or a water tank for

the storage component. Important design parameters include collector area and orientation, building heat loss, collector and heat-exchanger efficiencies, storage capacity, and storage-to-room coupling. The coupling and storage capacity are critical factors in an active charge/passive discharge system. If either is too small, the storage component will get too warm, resulting in poor system performance and an uncomfortable interior environment.

Seven figures and five tables complement the text. The computer code for the developed method is included in the appendix.

Conclusions: The simple analysis method predicts annual solar fraction with a standard error of three percent with respect to TRNSYS simulations.

The performance of active charge/passive discharge designs is comparable to active and passive designs in a range of climatic conditions. System costs show an economic advantage over active systems, but active charge/passive discharge systems are less certain to be competitive with passive systems. Benefits include integration of heating components with structural members, contribution to cooling and hot water loads, architectural flexibility, and comfort advantages.

Future work should seek more rigorous field validation and extension of the analysis method to systems that use air as the heat-transfer fluid.

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Electric Utility Value Determination for Wind Energy

David Percival
James Harper

Objective: Describe a method developed by SERI to determine the value of wind energy conversion systems (WECS) to electric utilities.

Discussion: The report consists of two volumes. The first volume describes the value determination method and discusses in detail each computer program available from SERI. The second volume is a user's guide for these computer programs.

The value determination process begins with the processing of weather data by the computer programs WTP (Weather Tape Preprocessor) or WEIBUL (Weibull Distribution Development) to produce hourly wind speed data or wind probability distributions, respectively. These data are then input to the program ROSEW (Representation of Solar Electrics — Wind), which estimates wind-derived electricity production. The results from ROSEW are then input to the program ULMOD (Utility Load Modifications) so that the WECS generation can be incorporated into the utility load forecast. The results are provided to the utility planning models. The expansion planning model

develops an optimum scenario of conventional generating unit additions. This number of conventional units is then given to a production cost model to develop a more accurate estimate of the variable operating costs needed for the conventional generating system. This cost information and the conventional capacity information from the expansion model for the base case (zero WECS) and for all the change cases (varying WECS capacity) are provided to the program FINAM (Financial Analysis Model). This final routine determines the break-even cost of each WECS penetration and the WECS marginal value, where value is the utility's present worth savings of reduced operating costs and modified capital additions. These values may then be combined with total WECS cost to determine the maximum amount of WECS capacity that can be economically added to the utility system.

Conclusions: The developed wind energy value determination method should be valuable for utility planning groups.

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Solar Report Summary

Issued November 1982

Open-Cycle Systems Performance Analysis Programming Guide

Douglas A. Olson

Objective: Describe how to write component subroutines for an open-cycle ocean thermal energy conversion (OC-OTEC) systems performance algorithm programmed on the SERI computer, and describe how to use the performance algorithm.

Discussion: An algorithm has been developed to calculate the performance of a Claude-cycle, OC-OTEC plant. The algorithm models the Claude-cycle system to consist of a flash evaporator, a turbine, a condenser, a deaerator, a condenser gas exhaust, a cold water pipe, and cold and warm seawater pumps. Each component in the OC-OTEC plant is represented by a separate subroutine in the computer program. The algorithm may be used to study the effects of different types of components, such as evaporators or condensers, on total system performance.

The report describes how to write the component subroutines, with the appropriate variable names and common statements, to fit into the computer program. The appropriate common blocks and input and output variables are listed for each subroutine. The main program which guides the subroutines is described, along with the input parameters for the main program. Finally, the thermodynamic functions which are preprogrammed in the algorithm are described.

Sixteen figures and seven tables are included. Nine appendices present the detailed computer code.

Conclusions: The details given in this report should facilitate use of the OC-OTEC performance analysis algorithm.

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Solar Report Summary

Issued June 1986

A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces

Richard E. Bird
Roland L. Hulstrom

Objective: Present the Bird model, a simple broadband model for direct and diffuse insolation under clear sky conditions, and compare it with five published broadband models.

Discussion: To properly design a solar energy system for a location lacking an insolation data base, insolation models are required. Insolation models have proliferated to the point where it is difficult for a solar user to decide which model to use. A detailed comparison is made for several simple broadband insolation models currently in use, and based on this comparison, a simple clear sky model for direct and diffuse insolation is formulated.

Nineteen figures and twelve tables are included. Tabulated model data are presented in an appendix.

Conclusions: All of the simple models considered provide results that agree within ten percent with the results from rigorous radiative transfer codes when the sun is in the zenith position. However, the Bird model is as accurate as any of the considered models and is the easiest to apply.

Future work should include comparisons with carefully taken insolation and meteorological data and should include cloud effects.

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Solar Report Summary

Issued November 1982

Solar Spectral Measurements and Modeling

Richard E. Bird
Roland L. Hulstrom

Objective: Describe a new spectroradiometer for routine measurement of the solar spectra and discuss new spectral modeling capabilities.

Discussion: SERI has directed the development of a unique solar spectroradiometer. A computer controls the instrument and provides data reduction and analysis. A complete spectrum from 300 to 2500 nanometers can be recorded in 2 minutes, 25 seconds.

In addition SERI has implemented a rigorous radiative transfer code for modeling solar spectra and for detailed radiation studies. The code uses Monte Carlo techniques to solve the equation of radiative transfer.

Data from this code are compared with those from two other codes, and a preliminary comparison is made between modeled and experimental data.

Seventeen figures are included in the report.

Conclusions: Measurements made with the new spectroradiometer appear to be of very high quality. Initial indications are that spectra from the SERI radiative transfer code will agree within eight percent with real spectra under the same atmospheric conditions. These new measurement and modeling capabilities have already proven to be extremely important to solar applications.

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Solar Report Summary

Issued November 1982

The Trade-Off Between Collector, Area Storage Volume, and Building Conservation in Annual Storage Solar Heating Systems

Sanford Sillman

Objective: Develop a comprehensive understanding of the performance of active solar heating systems with intermediate and annual-cycle storage.

Discussion: A daily-step computer simulation was used to determine the performance of solar heating systems as collector and storage sizes were varied. Simulations were performed for systems in four cities: Boston, Mass., Medford, Oreg., Bismarck, N. Dak., and Albuquerque, N. Mex. The study assumed various building load types and included both flat-plate and evacuated-tube collectors at different tilt angles, and single-tank and two-tank systems. A unique feature of the study was the investigation of active solar systems used to provide backup heat for passive solar and energy-conserving buildings as well as to meet standard building loads.

Seventeen figures and two tables are included. Three appendices contain details concerning the basic assumptions used in the study, building load data, and results of the simulations.

Conclusions: System performance increases linearly as storage volume is increased, up to the point where the storage tank is large enough to store all heat collected in summer. This point of "unconstrained operation" represents the optimum design for annual storage systems. In contrast to diurnal storage systems, annual storage show only slightly diminishing returns as system size is increased. Annual storage systems providing nearly 100 percent solar space heat may be economically preferable to the more common 50 percent solar heating systems with diurnal storage. In contrast to diurnal systems, annual storage systems perform well in meeting the load of a passive or energy-efficient building.

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Solar Report Summary

Issued November 1982

Yearly Average Performance of the Principal Solar Collector Types

Ari Rabi

Objective: Using hour-by-hour simulations from 26 meteorological stations, correlate, using curve fitting methods, the yearly total energy that can be delivered by the principal types of solar collectors.

Discussion: The solar collector types considered include flat plate, evacuated tubes, compound parabolic collectors, collectors that track about one axis, collectors that track about two axes, and parabolic central receivers.

The correlations are presented as polynomials of first and second order in yearly average insolation, latitude, and threshold heat loss for a given optical efficiency. With these correlations, the yearly collectible energy can be found by reading a single graph. This method reproduces the results of hour-by-hour

computer calculations with an accuracy of two percent for flat plates and two to four percent for concentrators.

Conclusions: The method can be applied to any system where the collectors operate year-round in such a way that no collected energy is discarded. This includes photovoltaic systems, solar-augmented industrial process heat systems, and solar thermal power systems. The method is recommended for rating collectors of different types of different manufacturers on the basis of yearly average performance. It is also useful for evaluating the effects of collector degradation, the benefits of collector cleaning, and the gains from collector improvements. For most of these applications, the method is accurate enough to replace a system simulation.

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Solar Report Summary

Issued September 1983

The Analysis of On-Site Use and Sellback in Residential Photovoltaic Systems

Sanford Sillman

Objective: Investigate the amount of electricity consumed on site and the amount of electricity sold to the utility by private residences with grid-connected photovoltaic systems.

Discussion: Grid-connected residential systems without batteries are a promising early use of photovoltaics. In these systems, photovoltaic power is used on site as much as possible, and the remainder is sold back to the utility. The amount of direct on-site use versus sellback of photovoltaic power depends on the instantaneous pattern of the building's electric load. In this study, a method is developed for characterizing the instantaneous load based on the on/off probabilities of individual appliances. This load characterization is then used to analyze on-site use and sellback. A simple photovoltaic simulation based on monthly time steps is designed for use with the instantaneous load characterization.

Simulations are then performed for a variety of building types and load mixes, including passive solar design and other conservation features. Fifteen figures and seven tables are included.

Conclusions: Results show that on-site use is much less, and sellback significantly more, than previous results indicated for single-family residences. Even small systems are found to sell back 50 percent or more of generated power to the utility. Simulations based on hourly load data show less sellback because hourly data do not reflect the instantaneous load. It is also found that on-site use is significantly greater for systems that serve multifamily units. Further investigation of the accuracy of the instantaneous load characterization is recommended. In addition, the methods developed could be used to investigate load management techniques and the use of battery storage in residential photovoltaic systems.

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Solar Report Summary

Issued September 1983

Daylight Availability Data for the United States

Claude L. Robbins
Kerri C. Hunter

Objective: To apply the Robbins and Hunter (R&H) model for generating daylight availability data to climate data in 81 cities in the United States.

Discussion: The R&H model, composed of simple algebraic expressions, is based on research at the SERI daylighting laboratory and is designed for low- and high-turbidity climates as well as for clear and overcast sky conditions. Inputs to the model are from

Typical Meteorological Year and Estimated Typical Meteorological Year data tapes. Data are presented in a format that permits them to be used easily on a city-by-city basis.

Conclusions: In the absence of measured daylight availability data for each city, this particular model closely matches measured values (Robbins and Hunter, **A Model for Illuminance on Horizontal and Vertical Surfaces**, SERI report no. TR-254-1703).

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Issued September 1983

Electric Utility Value Determination for Wind Energy

David Percival
James Harper

Objective: Describe a method developed by SERI to determine the value of wind energy conversion Systems (WECS) to electric utilities.

Discussion: The first volume of this report describes the value determination method and gives detailed discussion of each computer program available from SERI. The second volume is a user's guide for the computer programs.

The value determination process begins with the processing of weather data by the computer programs Weather Tape Preprocessor (WTP) or Weibull Wind Speed Distribution (WEIBULL) to produce hourly wind speed data or wind probability distributions, respectively. These data are then input to the program Representation of Solar Electric-Wind (ROSEW), which estimates wind-derived electricity production.

The results from ROSEW are then input to the program Utility Load Modification (ULMOD) so that the utility load forecast may be modified to incorporate

the WECS generation. These results are then provided to the utility planning models. The output from the planning models is fed to Financial Analysis Model (FINAM).

A program named Diversity Model (DIVERS) can be used to determine the effect of spatial diversity of the wind resource upon the WECS value.

The final output of this series of programs gives a financial value (dollars per kilowatt) of the wind energy system under consideration in a specific utility system.

Ten figures and ten tables are included in Volume I. Two related papers are included as appendices to Volume I. Volume II contains thirty-seven figures.

Conclusions: This set of programs should be valuable to utilities planners, and should be obtained by interested planning groups.

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Solar Report Summary

Issued June 1986

Objective: To formulate a simple spectral model for calculating solar irradiance that can be used on small computers and provide accurate results.

Discussion: A spectral model for cloudless days that uses simple mathematical expressions and tabulated look-up tables to generate direct normal and diffuse horizontal irradiance is presented. The model is based on modifications to previously published simple models and comparisons with

Beer's-Law-Based, A Simple Solar Spectral Model for Direct Normal and Diffuse Horizontal Irradiance

Richard E. Bird

rigorous radiative transfer codes. This model is expected to be more accurate and to be applicable to a broader range of atmospheric conditions than previous simple models. The prime significance of this model is its simplicity.

Conclusion: The spectral model can be used on small desk-top computers. The spectrum produced by this model is limited to 0.3 - 4.0 μm wavelength with an approximate resolution of 10 μm .

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Solar Report Summary

Issued September 1983

Steam Generation in Line-Focus Solar Collectors: A Comparative Assessment of Thermal Performance, Operating Stability, and Cost Issues

L. M. Murphy
E. Kenneth May

Objective: Assess the engineering and system benefits of using direct steam (in situ) generation in line-focus solar collectors.

Discussion: The major emphasis of the analysis presented is a detailed thermal performance comparison of in situ boiling systems with steam flash systems and unfired boilers using heat transfer fluids. Following a review of relevant two-phase flow research, the analysis model developed for this study is discussed in detail. Analysis of potential flow stability problems is provided along with a cursory cost analysis and an assessment of freeze protection, safety and control issues.

Seventy-six figures and eight tables are included. Five appendices present details of the system model, thermal fluid transport, properties of air and heat

transfer fluid, and the methodology for calculating annual energy delivery.

Conclusions: The direct boiling system has a significant thermal performance advantage over the conventional oil and flash systems, and flow stability does not appear to be a significant problem. At steam temperatures of 220° C (430° F) under the chosen set of assumptions, annual delivered energy predictions show that the in situ system can deliver 13 percent more energy than an oil system and 12 percent more than a flash system with the same collector field. The in situ system may result in a ten percent capital cost reduction. Other advantages of the in situ system include simpler control compared to flash systems, and fluid handling and safety improvements compared to oil systems.

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Solar Report Summary

Issued January 1985

Comparison of Model and Observations of the Wake of a MOD-0A Wind Turbine

J. C. Doran
K. R. Packard
Pacific Northwest Laboratory

Objective: To compare wind velocity measurements upwind and downwind from the MOD-0A wind turbine with model calculations.

Discussion: A MOD-0A wind turbine has been operated at Clayton, New Mexico, by the National Aeronautics and Space Administration for the U.S. Department of Energy since 1977. In a previous study, wake measurements made at an array of towers downstream of the turbine were analyzed. In this study, data were collected both upwind and downwind from the turbine to determine some of the characteristics of wakes within approximately two blade diameters of the machine. The data are presented for a number of cases. In these cases, a variety of wind conditions resulted in wakes measured at the tower array, or at

two additional towers located on the other side of the MOD-0A from the tower array. These data are compared with predictions of computer model, Wakewind, and an evaluation of the model's performance is given. Based on observations of co-flowing jets in fluids, Wakewind incorporates later modifications introducing additional effects arising from the profile drag of the turbine.

One table and 20 figures are included.

Conclusions: Generally, the computer model results agreed well with the measurements at wind speeds well below the rated speed of the MOD-0A, but the results were not as satisfactory at higher wind speeds.

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Solar Report Summary

Issued January 1985

Horizontal-Axis Wind System Rotor Performance Model Comparison: A Compendium

Aerospace Systems, Inc.
AeroVironment, Inc.
Oregon State University
United Technologies Research Center
Rocky Flats Wind Energy Research Center

Objective: To evaluate performance prediction methods for horizontal-axis wind turbines.

Discussion: This compendium consists of four reports. They were prepared by four separate contractors: Aerospace Systems, Inc., AeroVironment, Inc., Oregon State University, and United Technologies Research Center (UTRC). These contractors were to apply their prediction methods to two rotors, that of the Enertech Model 1500 turbine and that of the 1/3-scale UTRC eight-kilowatt turbine. Three of the contractors used a blade-element/momentum analysis, while the fourth (UTRC), used a lifting line/prescribed wake analysis. Results from the four prediction methods are compared with actual test data gathered

via Controlled Velocity Testing (CVT), performed by the Rocky Flats Wind Energy Research Center.

One hundred-sixty five figures are included. For each model, the computer code and sample model output are included.

Conclusions: For the Enertech 1500 turbine, the rotor performance predictions agreed with the CVT data. However, due to the lack of high tip speed data, verification of the Glauert momentum theory was not possible. Predictions for the UTRC 1/3 scale eight-kilowatt rotor did not agree with test results. The reasons cited for the discrepancies center on inadequate airfoil section data and the varying blade pitch angles of the UTRC flexbeam rotor.

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Solar Report Summary

Issued January 1985

SEACC: The Systems Engineering and Analysis Computer Code for Small Wind Systems

P. K. C. Tu

V. Kertesz

Rocky Flats Wind Energy Research Center

Objective: To describe the Systems Engineering and Analysis Computer Code (SEACC), a computer program for performance evaluation of small wind energy conversion (SWECS) systems.

Discussion: The SEACC, as developed by the Rocky Flats Wind Energy Research Center, evaluates complete horizontal-axis SWECS performance. Rotor power output as a function of wind speed and energy production at various wind regions is predicted by the code. Efficiencies of components such as the gearbox, electric generators, rectifiers, electronic inverters, and batteries can be included in the evaluation process to reflect the total system performance. Parametric studies can be performed for blade design characteristics such as airfoil series, taper rate, twist degrees, and blade pitch setting; and for geometry such as rotor radius, hub radius, number of blades, coning angle, and rotor rpm. Design tradeoffs also can be included to optimize system configurations for constant rpm, constant tip-speed ratio, and rpm-specific rotors. SWECS energy supply relative to the load

demand for each hour of the day and during each season of the year can be assessed by the code if the diurnal wind and load distributions are known. Blade aerodynamic loading information is also available during each computer run of the code.

Five tables and 21 figures are included. Three appendices present a user's manual, and listings of the code. A table of nomenclature explains abbreviations and technical terms used.

Conclusions: SEACC has proven to be an efficient SWECS research, development, and design tool. Preliminary configuration design trade-offs and parametric studies can now be performed with minimum computer costs. With rotor geometry and blade airfoil aerodynamic data, major rotor performance can be determined with the code. When subsystem efficiencies are known, SWECS system performance can be predicted. Energy matching/mismatching questions between SWECS supply and load demand can be answered when the local diurnal wind and load profiles are available.

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Solar Report Summary

Issued January 1985

Vertical Axis Wind Turbine Control Strategy

Gerald M. McNerney
Sandia National Laboratories

Objective: To present a computer model that uses wind data and operational data to calculate the power produced by a vertical axis wind turbine (VAWT).

Discussion: Algorithm control strategy for unattended wind turbine operation at the low wind speed cut-in condition is an important aspect of wind energy production that has not previously been fully considered. Early experience in automatic operation of the Sandia seventeen-meter VAWT has demonstrated the need for systematic study of control algorithms. Accordingly, a computer model has been developed that uses actual time-series wind data and turbine performance data to calculate the power produced by the Sandia VAWT operating under automatic control.

The model has been used to investigate the influence of turbine starting algorithms on annual energy production.

Following a brief introduction, the computer model and supporting algorithms are discussed. The application of algorithm control to the economics of VAWT operation are discussed, and the results of the modeling are generalized to obtain general guidelines for control algorithm design.

Twelve figures are included.

Conclusions: The model can be used to select control algorithms and threshold parameters that maximize long-term energy production.

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Solar Report Summary

Issued January 1985

A Vortex Model of the Darrieus Turbine: An Analytical and Experimental Study

J. H. Strickland
T. Smith
K. Sun
Sandia National Laboratories

Objective: To describe recent improvements in the vortex model of a Darrieus wind turbine.

Discussion: The vortex model appears to be capable of adequately predicting blade loading and wake structure for a Darrieus wind turbine, but it has previously required excessive computer time to run. The heavy computer time requirement has limited the utility of the model. The purpose of the work reported in this paper was to enhance the utility and credibility of the vortex model, and to pursue a reduction of the computer time necessary to run the model. Following a brief introduction, the aerodynamic model is dis-

cussed, methods for reducing the computer time requirements are presented, and the supporting experimental work is recounted. The analytical results are compared to the experimental data.

The computer code and supporting data are presented in four appendices. Twenty-eight figures are included.

Conclusions: The reported vortex model, along with the reduced computer time required for running it, provides a valuable analytical tool for Darrieus wind turbine designers.

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Solar Report Summary

Issued December 1986

Development of an Analytical Model and Code for the Flapping Response of a HAWT Rotor Blade: A Subcontract Report

R. W. Thresher
E. L. Hershberg
Oregon State University

Objective: Develop a computer-modeling technique to adequately estimate flapping in rotor blades, for use on horizontal-axis wind turbines.

Discussion: Before the development of FLAP (force and loads analysis program), it was difficult to estimate the deformation of a wind-turbine blade. This report discusses the theoretical development of a code to estimate blade flapping, discusses the user characteristics of the program, and provides a program listing and sample run. The present program allows for the analysis of mean wind, wind sheer, and tower shadow. The program was designed to be easily modified to accommodate future additions of dynamic stall and wind-turbulence factors. Although the program can analyze up to four sets of coordinate shape functions, the analysis that is presented, and the most common application, will be to use only one function/one flap degree of freedom. The computer program was segmented into two major parts: a data preprocessor that takes the raw-blade parameters and turbine-property files and creates a data file, and a second module that actually solves the equations, computes the loads, and prints the results. Eleven blade properties are required as input to the preprocessor. The

program then computes the blade configuration for 21 equal-sized blade sections. The results of the computation provide nine resultant quantities: blade section flap displacement, flapwise slope, flap velocity, blade tension, blade torsion, blade edgewise sheer and moment, and blade flapwise sheer and moment.

An analysis of the flapping on a Grumman three-blade wind turbine was compared to actual operational results. Test data from the U.S. Department of Energy wind testing site were used. The programs are menu-driven and purported to be user friendly. Substantial documentation is included in the program. The report includes 14 figures and 3 tables. Formulas for the calculation of all important variables are included.

Conclusions: When comparing the estimated and measured data, some difficulties appeared in the analysis of the tower shadow, but the overall analysis was quite close to the measured values. The computer code is not considered validated because of the comparison with only one machine. Additional analyses should be done on machines with less rigid blades.

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Solar Report Summary

Issued June 1986

Objective: Present formulas that provide reliable estimates of the transmittance of a solar beam propagating between a heliostat and a receiver.

Discussion: The atmospheric attenuation of a reflected solar beam is a significant factor in the optical analysis and optimization of a large solar central receiver system. The formulas presented in the report are designed to measure this energy loss, and they are wavelength-independent, functional fits to the tabulated results of Vittitoe and Biggs, which, in turn, are the results of numerical integrations of spectral transmittance data calculated with the aid of the computer code LOWTRAN 3. The formulas allow for interpolation and extrapolation and have a form characteristic of atmospheric transmittance models.

Two models are presented in the publication: a transmittance model, which contains five explicit physical variables, and a loss model, which contains three implicit physical variables.

Two computer programs (HART and CAT) implement the transmittance model, and a user's guide to

Atmospheric Transmittance Model for a Solar Beam Propagating between a Heliostat and a Receiver

Charles L. Pitman

Lorin L. Vant-Hull

the computer programs developed for this project is included in the report. All the programs are written in FORTRAN.

Eight tables and nine figures accompany the text. There are also three appendices: the first concerns irradiance and intensity, the second discusses the variables used in the quantitative description of atmospheric conditions, and the third lists the FORTRAN codes that were developed to implement the equations and methods described in the report.

Conclusions: Formulas are derived for the atmospheric transmission of a solar beam propagating between a heliostat and a receiver atop a tower. The functional fits presented in the report agree to within about 1% energy loss with the tabulated results from which they were derived. These formulas also allow for interpolation and extrapolation and provide meaningful results for any values of the input parameters that are significant to solar central receiver systems.

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Solar Report Summary

Issued April 1989

Objective: Examine the effects of building orientation on the heating and cooling loads of residential buildings across the United States.

Discussion: The study examines the impact of orientation on both the heating and cooling loads of a prototype building. The authors used a computer analysis tool BLAST (Building Loads Analysis and System Thermodynamics) to model the thermal characteristics of the buildings oriented in various directions in various climates. The prototype building has the majority of the glazing facing to the south, coupled with some overhang for shading. A small amount of glazing (25% of the south glazing) is also located on the north side. The east and west sides have no windows. Parametric analysis was done by rotating the building and comparing the thermal loads on the building in 25 various climates. The results are presented as a variation from the south orientation for all locations studied. The analysis from each climatic zone is balanced between the heating and cooling loads to provide an overall figure for the load on the building. In addition to analyzing the 25 locations in general, four representative locations were examined more extensively. Sensitivity analysis was also completed on building factors that might influence the

The Impact of Building Orientation on Residential Heating and Cooling

B. Andersson
W. Place
R. Kammerud
M. P. Scofield

results. Glazing size, shading, and thermal mass were examined independently.

The paper contains 11 figures and one table. The final version of the paper was printed in *Energy and Buildings*, Vol. 8(1985) pp. 205-224.

Conclusions: In all but the very hot climates, the south orientation produced the lowest overall loads. The east and west orientations produced the highest loads: the total loads were increased from 10-20% in the northern U.S. to 30-70% in the desert southwest over south orientations. North orientation produced higher loads than south in all but the hottest climates. Total building loads for north orientations rather than south orientations were 25-45% higher in the high desert areas where solar heating benefits are large, 5-20% in the majority of the country and produced decreases by up to 12% in the very hot southerly climates.

These results suggest that planning and zoning officials should encourage builders to orient buildings with the long sides facing north and south, and to place the majority of the glazing on the south, except in the very hottest climates. Developers should also consider these effects when establishing subdivision design.

How to Order Publications

Andersson, Brandt; Place, Wayne; Kammerud, Ron; Scofield, M. Peter. (August 1985). "The Impact of Building Orientation on Residential Heating and Cooling." *Energy and Buildings*, Vol. 8 (No. 3); pp. 205-224. Avail-

able from Elsevier Science Publishers, 52 Vanderbilt Avenue, New York, N.Y. 10017.

Solar Report Summary

Issued April 1989

Silica Gel Sorption Properties under Adiabatic Conditions

A. A. Pesaran
K. Choudhury

Objective: Modify the SERI Sorption Test Facility from isothermal operation to adiabatic operating conditions and measure the adsorption/desorption characteristics of silica-gel-coated, parallel-channel geometry as a function of operating conditions and aspect ratio under adiabatic conditions.

Discussion: Single-blow experiments were performed on two, single-passage test cells with different aspect ratios and different air flow rates and inlet conditions. The first test cell, from FY 1983 studies, had an aspect ratio of 0.0095. The second test cell, fabricated for this study, has an aspect ratio of 0.0454. Tests were performed at flow rates of 200, 400, and 500 cm³/min, a pressure of 1 atm, temperatures of 23°-25°C, and absolute humidity ratios of 0.001-0.018 kg/kg. Both adsorption and desorption runs were performed.

This report contains 17 figures and three tables. The appendix shows breakthrough data for each experiment.

Conclusions: As the air flow rate and aspect ratio increase when other parameters are kept constant, the desiccant matrix loses its sorption capacity faster. The test cell operated near isothermal conditions rather than adiabatically because the test cell walls had a large thermal mass compared with the amount of desiccant used. Since constructing single-passage test cells with small thermal masses that can be operated adiabatically at the Sorption Test Facility is difficult and possibly not practical, further testing at this facility will be used primarily for isothermal operation. The adiabatic experiments can best be done with multipassage test cells having small thermal masses relative to desiccant mass. A single-blow test facility for performing experiments with multipassage test cells was fabricated in an FY 1984 Heat and Mass Transfer Analysis task and experiments were performed in an FY 1985 desiccant project.

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Solar Report Summary

Issued April 1989

Modeling High-Temperature Direct-Contact Heat Exchange in an Irrigated Packed Bed

M. S. Bohn

Objective: Develop an analytical model that describes the heat transfer performance of a direct-contact heat exchanger operated as an irrigated packed bed at high temperature.

Discussion: Direct-contact heat exchange can provide a cost-effective means of transferring heat between a gas and a liquid in applications where the gas and liquid do not react and can be separated after the heat exchange is effected. An especially attractive application is the production of high-temperature air from molten salt in a solar thermal central receiver system. The particular configuration of interest here is an irrigated packed bed in which the liquid is introduced at the top of a random bed of packing elements and flows in rivulets down the bed transferring heat to a counterflowing stream of gas. Experimental data and analytical models that describe the heat transfer performance of such a heat exchange device are lacking. This hampers efforts to determine the economic value of direct-contact heat exchange and to design commercial-sized systems.

In response to this problem, the present work was undertaken to provide an analytical model of direct-contact heat exchange. In addition to allowing commercial-sized design and comparison and extrapolation with experimental data, this model was developed to point out the important heat transfer mechanisms and to point the way to required future research. The model expands on existing models in that it uses the heat and mass transfer analogy and determines heat transfer at the gas-liquid interface

via mass transfer correlations. Other modes of heat transfer, notably conduction in the bed packing, convection from dry portions of the packing to the gas, and radiation heat transfer, were added to the mass transfer correlations. Where available, correlations from the literature were used for calculating the contributions of the various heat transfer mechanisms.

The document contains 13 figures and 2 tables.

Conclusions: The model shows that radiation heat transfer is negligible (relative to the convective contributions) even at temperatures up to 1100°C and for large commercial-sized packing. This is consistent with available data at high temperature and simplifies the analysis considerably. The effect of variable properties can be handled in a simple manner. Comparing the resulting model with available data for a low-temperature oil and air system, it was found that the model resulted in much better agreement with the data relative to previous models. Depending on the type of packing and how well it was wet by the liquid, the conduction in the packing has a relatively small effect but does tend to increase the heat-transfer rate predicted by the model closer to the data. Favorable agreement was also seen with an air and molten salt system, although little data were available for comparison. The model is not applicable to liquids that do not wet the packing because it relies on a wetting correlation developed for wetting liquids. For the air and molten salt system, it appears that volumetric heat transfer coefficients of 6,000-12,000 W/m³ °C can be achieved.

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Solar Report Summary

Issued April 1989

Objective: Experimentally characterize the performance of rotary desiccant dehumidifiers and develop and validate analytical methods for evaluating their performance in air-conditioning systems.

Discussion: Experiments were aimed at developing a basic understanding of the simultaneous heat and mass transfer processes in rotary dehumidifiers. Two dehumidifier test articles were tested under cyclic operation to fully characterize their performance. Detailed accounts of SERI's Cyclic Test Facility, its hardware and instrumentation, the two test articles, data generated on the test articles, and data reduction and analyses methods are provided in this report. The data provide an engineering data base for evaluating rotary dehumidifiers for cooling applications.

This report contains 35 figures, nine tables, and nine appendices.

Conclusions: For a simple low-pressure-drop geometry, such as the parallel plate, ensuring and maintaining a uniform air passage gap is critical to obtaining high performance. The tests reported here indicate that non-uniform passage spacing, in which 48% of the passages possess gaps ranging from 0.08 to 1.92 times the design gap, resulted in about a 50%

Experimental Studies of Heat and Mass Exchange in Parallel-Passage Rotary Desiccant Dehumidifiers for Solar Cooling Applications

D. Bharathan
J. M. Parsons
I. L. Maclaine-cross

reduction in the overall number of transfer units for dehumidification from the nominal design value of 10.

Low-speed and high-speed test results correlated well with the analogy theory, while medium-speed results deviated significantly from this theory. A nonlinear analogy method incorporating a linear variation of the matrix capacity was adopted to analyze the medium-speed results, with satisfactory agreement.

The effective gel mass in the matrix was found to be 63% of the total gel mass. Independent static tests confirmed this finding. The dehumidifier's performance, as measured by the effectiveness, agreed with theory to within $\pm 10\%$. This work represents the first attempt to compare a detailed component model for a rotary desiccant dehumidifier with a complete set of experimental data relevant to solar cooling applications.

The Cyclic Test Facility at SERI can be used to further improve the theoretical model for other desiccants and geometries. The model will help designers determine the trade-offs that must be made among such design characteristics as pressure loss, mass-transfer performance, cost, reliability, and aging.

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Solar Report Summary

Issued April 1989

Experimental Study of an Advanced Silica Gel Dehumidifier

D. Bharathan
J. M. Parsons
I. L. Maclaine-cross

Objective: Characterize, experimentally, the performance of an advanced, rotary, desiccant dehumidifier and develop and validate analytical methods for evaluating its performance in air-conditioning systems.

Discussion: A series of experiments was undertaken to develop a basic understanding of the simultaneous heat and mass transfer processes in rotary dehumidifiers. An advanced dehumidifier test article was tested under cyclic operation to fully characterize its performance. Brief accounts of SERI's Cyclic Test Facility, with its hardware and instrumentation, and detailed accounts of the test data and data reduction and analyses methods are provided in this report. The data provide an engineering data base for evaluating rotary dehumidifiers for cooling applications.

The report contains 21 figures, seven tables, and eight appendices.

Conclusions: For a simple, low-pressure-drop geometry, such as the parallel plate, ensuring and maintaining a uniform air passage gap is critical to obtaining high performance. Tests of the dehumidifiers indicated that non-uniform passage spacing (30% of the passages possessed gaps rang-

ing from 65%-135% of the design gap) resulted in a 40% reduction in the overall number of transfer units for dehumidification from the nominal design value of 10.

Results of both low-speed and high-speed tests correlated well with the analogy theory, while results of medium-speed tests exhibited significant deviations from this theory. A nonlinear analogy method incorporating a linear variation of the matrix capacity was adapted to analyze the medium-speed test results, with satisfactory agreement. Dynamic tests indicate that about 60-65% of the total gel present in the matrix was active; static tests show this fraction to be 75%.

The dehumidifier's performance, as measured by the effectiveness, agreed with theory to within $\pm 10\%$. This work represents the successful validation of a detailed component model for a rotary desiccant dehumidifier.

The Cyclic Test Facility at SERI can be used to further improve the theoretical model for other desiccants and geometries, so that appropriate trade-offs among such important design components as pressure loss, mass transfer performance, cost, reliability, and aging can be made.

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Social Science & Consumer Affairs

19 Social Science &
Consumer Affairs

Standards, Tests & Measurements

Standards, Tests & Measurements

SERI Report Summary

Optical Analysis and Optimization of Line Focus Solar Collectors

P. Bendt
A. Rabl
H. W. Gaul
K. A. Reed

Objective: Describe a macroscopic approach that yields all the parameters needed for the optical design of line focus parabolic troughs in closed analytical form, requiring minimal computation.

Discussion: The goal of the optical analysis discussed in this report is to determine the flux at a solar receiver as a function of concentrator configuration, receiver size, width of sun, and optical errors. All causes of image spreading are reported in terms of angular standard deviation. Ray tracing with a real reflector and a real sun is shown to be equivalent to convoluting the angular acceptance function of a perfect concentrator with an effective radiation source. This effective source is obtained by convoluting the distribution function of optical

errors with the angular profile of the sun. The problem is reduced to two dimensions by projecting the three dimensional motion of the sun on the plane normal to the tracking axis. In this frame the apparent width of the sun is inversely proportional to the cosine of the incidence angle.

Ten figures and 11 tables accompany the text. A detailed appendix discusses typical insolation values for use in optimization analysis.

Conclusions: By using the self-contained users guide included in the report, the results of this report may be applied to the optical design of line focus solar collectors.

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SERI Report Summary

Effect of Circumsolar Radiation on Performance of Focusing Collectors

P. Bendt
A. Rabi

Objective: Calculate the effect of circumsolar radiation on both the instantaneous and the long-term average performance of focusing collectors.

Discussion: This report discusses the measurements obtained by Lawrence Berkeley Laboratory to define the effect of circumsolar radiation on the performance of focusing collectors. Beginning with a section explaining nomenclature and definitions, the report presents a review of the optical analysis and physics involved. Then, after reviewing the methods used for measurement and quantification of solar radiation, the numerical techniques and validation of the models used are discussed.

The report is well illustrated and documented, with eight figures and six detailed tables.

Conclusions: The report shows that the long-term average effect of circumsolar radiation can be calculated by means of a single, standard circumsolar scan. The approach used was found to have an rms error of only 0.2 percent, negligible compared with typical uncertainties in system performance calculations. Long-term average circumsolar ratio is a simple, useful measure of circumsolar radiation. Extensive tables show the effect of circumsolar radiation on parabolic troughs and dishes. In typical cases, the effect requires a correction of a few percent.

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SERI Report Summary

Materials Analysis Methods for Examination of Solar Cells

C. N. Wilson

Objective: Describe the set of materials analysis techniques available to SERI under a contract with the Handford Engineering Development Laboratory (HEDL) and provide a "user's guide" for these services.

Discussion: HEDL provides materials analysis services to SERI for characterization of materials used in SERI photovoltaic research and development programs. Eight analysis techniques available from HEDL are discussed:

- auger electron spectroscopy,
- ion microprobe mass analysis,
- electron microscopy,
- electron probe microanalysis,
- x-ray fluorescence analysis,
- x-ray diffraction,
- spark source mass spectrometry, and
- neutron activation analysis.

For each technique, the following information is included:

- associated equipment,
- operational principles,
- instrument capabilities,
- limitations and accuracy,
- specimen requirements,
- application to photovoltaics,
- data format, and
- comparison with other analytical methods.

The text is complemented by 11 figures and eight tables. Four appendices include a bibliography of references on the eight techniques presented, a glossary of acronyms routinely used in the materials analysis discipline, a listing of common units and conversion factors, and the periodic table.

Conclusions: A comprehensive array of materials analysis services is available to SERI through the HEDL contract.

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SERI Report Summary

Advanced Component Research Facility (ACRES)

Mark Bohn

Objective: Describe the SERI Advanced Component Research Facility (ACRES).

Discussion: The SERI ACRES facility centers around two Omnium-G solar concentrators. The equipment is available for use in various research programs at SERI.

This report presents a detailed description of the ACRES facility. The Omnium-G concentrator, the tracking electronics, and the Omnium-G steam

loop/electrical generating equipment are described as background. Conversion of the equipment into a flexible, high-temperature test loop and optical test concentrator is described.

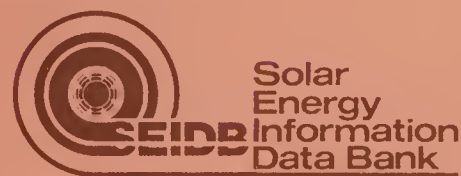
Nine figures accompany the text.

Conclusions: The SERI ACRES facility supplies the necessary capability to research components related to point-focus solar collectors.

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SERI Report Summary

Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses

Cecile Leboeuf

Objective: Present a set of inputs, assumptions, analytical methods, and a reporting format for use in residential and commercial solar system analyses.

Discussion: The use of standard inputs and methods should facilitate the comparison of results of analyses performed by different investigators. By the common use of load data, meteorological data, economic parameters and reporting format, researchers examining different types of solar equipment may more easily compare their results. In this approach, only parameters not directly related to the energy system of a building are specified (with the exception of passive systems, in which the building is an integral part of the energy system), so that no biases are introduced into the analysis. In addition, a variety of climates are characterized that are typical of those found in the United States.

For residential heating and cooling systems, three locations are discussed: Fort Worth, Tex.; Madison, Wis.; and Washington, D.C. The weather data used to characterize these cities are the TMY

(Typical Meteorological Year) because of their ability to typify the long-term average conditions. A house for each location is defined that is typical of new construction in that locale. Hourly loads are calculated using a computerized load model which interacts with the system and other specified inputs that characterize each house. Using the inputs and analysis tools recommended in this report, examination of thermal and economic performance of a particular system in each of the chosen locations will indicate the climate types that the system is most compatible with.

For commercial cooling analyses, four locations were chosen: Washington, D.C.; Phoenix, Ariz.; Fort Worth, Tex.; and Miami, Fla. A light commercial office is used for analysis in all four locations. Hourly cooling and heating loads were computed for each city and stored on magnetic tape.

Conclusions: Consistent adherence to the analysis guidelines presented will help researchers, component and system designers, and policy makers to commercialize solar energy.

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SERI Report Summary

Statistical Problems in Design Technique Validation

Joel S. Cohen

Objective: Review and analyze the statistical validation process for measuring the accuracy of design techniques for solar energy systems.

Discussion: The report begins with a discussion defining the validation of design techniques. This is followed by an assessment of the statistical variability inherent in the design and measurement processes and the way in which this variability can dictate the choice of data, accuracy of the results, and choice of questions that can be accurately answered by such processes. The approach used by the author is primarily concerned with design procedure validation in a realistic context, where the discrepancy between measured and predicted results is due to limitations in the mathematical models used in the procedures and the inaccuracies of the input data.

A set of guidelines for successful validation methodologies is discussed, and a simplified validation method for domestic hot water heaters is presented.

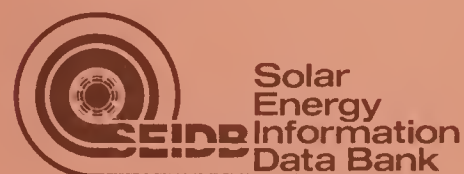
One figure and one table are included in the report.

Conclusions: It is important to evaluate design technique performance in the context of the realistic process of system design. It is not possible to perform an accurate statistical validation study if the process is expected to produce accurate error estimates for all variables of interest for all the different solar systems on the market. The scope of any study must be confined to system variables that can be carefully monitored.

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SERI Report Summary

STAM: SERI Standard Module for Collector Evaluation

Jim Castle

Objective: Describe the steps being followed in the development of the STAM (Standard Module) facility at SERI.

Discussion: The STAM facility will be capable of supplying a working fluid, under carefully controlled temperature and flowrate conditions, to various solar collectors that may be connected to the facility. This capability will be used in such areas of investigation as collector thermal performance, materials testing, and reliability studies. Initially, emphasis will be on using the facility to evolve a standard testing procedure for quantifying the thermal performance of concentrating solar collectors.

This report examines the details of the projected facility, including research needs to be satisfied,

technical specifications, manpower requirements, location of the site, and costs.

Appendix A is the Module Procurement Specification Document, which gives the specifications to be fulfilled by the contractor selected to design and construct the STAM facility.

Six figures complement the text.

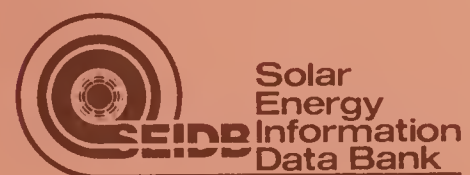
Conclusions: The STAM equipment will permit measuring the useful energy generated in a solar collector via the conventional procedure described in ASHRAE 93-77, as well as by the calorimetric technique which offers special advantages at higher operating temperatures.

The STAM facility will be a valuable tool for several branches in the SERI Research Division.

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SERI Report Summary

Determining the Optical Quality of Focusing Collectors Without Laser Ray Tracing

Paul Bendt
Harry W. Gaul
Ari Rabl

Objective: Describe a method for evaluating the optical quality of focusing solar collectors without using laser ray tracing.

Discussion: This paper describes a novel alternative to laser ray tracing techniques for evaluating the optical quality of focusing solar collectors.

After presenting the theory behind optical-quality testing, the test results for a parabolic trough collector with a cylindrical receiver are presented. According to the report, the reproducibility of the technique presented is good, on the order of plus or minus 5 percent.

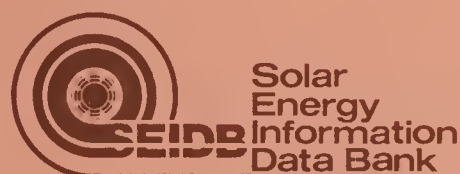
In the proposed method, an angular scan is made of the collector, i.e., the collector output is measured over the entire range of angles for which there is measurable output from the collector. The output is then compared with the calculated output.

Conclusions: The optical quality of a focusing collector can be determined by measuring the performance over a range of angles and then comparing the data with calculated results. The advantage of this method is that it does not require any equipment beyond that which is used for measuring collector efficiency.

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SERI Report Summary

Summary of the DPR

J. Easterling
A. Grace
R. Kettle

Objective: Provide reference that categorizes recommendations of the Domestic Policy Review (DPR) of solar energy.

Discussion: Policy makers and program planners can use this reference to determine if their specific recommendations are consistent with the broader recommendations of the DPR.

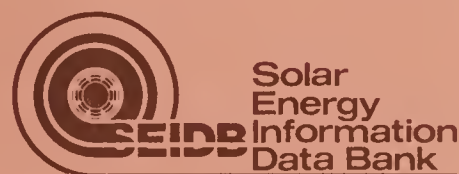
The text contains a brief history of DPR and lists assumptions used and barriers identified by each DPR panel.

Conclusions: DPR recommendations summarized and resulting administration-adopted recommendations are presented in table form.

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SERI Report Summary

The Implementation of State Solar Incentives: Testing and Certification Programs

Robert Odland

Objective: Examine the experience of several states with the implementation of solar testing and certification programs.

Discussion: The experiences of California, Florida, Minnesota, and Oregon are examined. Only California and Florida have formal testing and certification programs. At the time of publication, both programs were voluntary, although certification of flat-plate collectors was to be required in Florida after January 1, 1980, and certification of collectors was being considered as a condition for state income tax credit in California. Minnesota has a system whereby the characteristics of solar equipment must be disclosed to the buyer. The manufacturer is responsible for developing the necessary infor-

mation. Oregon has several programs which require "qualifying standards" or criteria to be developed for solar equipment.

Conclusions: Testing and certification of solar collectors are here to stay, and similar programs for other components probably will be developed. Testing serves a very important function for manufacturers as well as for consumers. Certification provides the mechanism for reporting test results. State involvement in testing and certification probably will decrease as national programs are developed.

For future programs, legislation should specify how the testing and certification will be implemented.

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Standards, Tests & Measurements

SERI Report Summary

Issued June 1981

Standards, Buildings Codes, and Certification Programs for Solar Technology Applications

Julia D. Riley
Robert Odland
Helen Barker

Objective: Explain the development of standards, building code provisions, and certification programs for emerging solar technologies.

Discussion: This report examines the relevant development processes in both the private sector and government. It is directed primarily at three audiences: federal officials in solar programs, participants in the development processes, and state and local officials. General emphasis is on federal policies and the traditional institutional framework within which those policies are developed.

Sections 1 through 4 describe the development processes. In each section, the nomenclature, participants, and philosophies associated with those processes are discussed. In Section 5 the processes involved in commercialization of solar technologies are discussed, and Section 6 examines

the development of policies for federal programs.

Appendix A reviews selected state and local activities. Appendices B through H discuss standards, building codes, and certification for various solar technologies. Appendix I contains an Office of Management and Budget circular on government employee participation in the voluntary consensus system. Appendix J contains excerpts from a contract to develop a model standards document for solar heating and cooling applications.

Conclusions: Policy planners should be aware that lack of careful planning can lead to a proliferation of standards, codes, and programs with conflicting requirements. Government support of standardization activities indicates a merging of private and public sector interest to solve the problems associated with standards, codes, and certification in solar technologies.

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SERI Report Summary

Issued June 1981

Long-Term Average Performance Benefits of Parabolic Trough Improvements

Randy Gee
Harry W. Gaul
David Kearney
Ari Rabl

Objective: Quantify the relative merit of eight near-term technological advances in improving the long-term average performance of parabolic trough concentrating collectors.

Discussion: The annual energy delivery of a parabolic trough collector using each of eight recent technological advances is calculated and compared to that of a reference parabolic trough. A detailed parabolic trough performance model is used in conjunction with a utilizability method based on long-term average meteorological data. The reference trough is typical of commercially available collectors. The eight improvements considered are:

1. selective coating absorptance increased to 0.98,
2. selective coating emittance decreased to 0.05 (at 100°C), and 0.15 (at 300°C),
3. back-silvered glass reflector,
4. concentrator slope error reduced to 3 mrad,
5. evacuated annulus receiver,

6. xenon back-filled annulus receiver,
7. heat mirror coated receiver glazing (emittance = 0.15, transmittance = 0.94), and
8. receiver glazing transmittance increased to 0.96.

The ratio of the energy delivery of each improved trough to that of the reference trough is defined as the normalized performance index (NPI). The NPI of each trough is presented in graph form for north-south, east-west, and polar-mounted troughs.

This report is also presented in a 12-page conference version, SERI/TR-333-462.

Conclusions: Substantial annual energy gains are shown to be possible with improved parabolic troughs. The performance improvement is strongly dependent upon operating temperature. Of the improvements considered, the use of stable back-silvered glass reflective surfaces promises the largest performance gain below 150°C. Above

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150°C, the development of trough receivers that can maintain a vacuum is the most significant potential improvement. Reduction of concentrator

slope errors also will deliver substantial performance improvement at high operating temperatures.

SERI Report Summary

Issued June 1981

SERI Laser Scanner System

Richard J. Matson
Theodore W. Cannon

Objective: Describe a laser scanner system (LSS) which can be used to map variations in the photoresponse of a semiconductor devices, specifically solar cells.

Discussion: The LSS produces a map of the photoresponse of a semiconductor by scanning a laser beam over the surface of the photosensitive device while the photoresponse of the device is displayed on a cathode ray tube (CRT) as a function of the laser beam's position. The photoresponse map of a solar cell can be used to identify solar cell faults such as microcracks, metallization breaks, regions of poor contact, and variations in emitter sheet resistance. The SERI LSS is patterned after an LSS unit described in the

National Bureau of Standards (NBS) Special Publication 400-24, "A Laser Scanner for Semiconductor Devices," by D.E. Sawyer and D.W. Berning. The present report assumes that the reader is familiar with the NBS publication. The modifications introduced in the SERI LSS are described, and the optical and electrical systems of both systems are discussed.

Nine figures and one table complement the text.

Conclusions: The most notable difference between the two systems is the SERI substitution of commercially available modular electronics for the discreet component circuitry used in the NBS LSS.

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Solar Report Summary

Issued November 1982

Inexpensive Thermographic Techniques for Determining Reliable Solar Collector Array Performance

A. Eden
T. Haverty

Objective: Discuss the use of relatively inexpensive thermographic equipment and techniques to detect typical flow problems hampering reliable performance in solar collector arrays.

Discussion: For solar collector arrays to be useful in solving energy supply problems in residential and commercial buildings, the arrays must be dependable and require little or no maintenance. Early detection of a blockage or other problems in the flow pattern of the array is essential to the continued operation of the entire collection system and also to the solar energy supply system.

Thermography may be used to detect flow problems in solar collector arrays. However, this approach has been hampered by the use of expensive thermographic tools and highly qualified technicians. In 1980, SERI researchers explored the requirements of both equipment and personnel to determine if it was possible to use less expensive equipment and less experienced personnel.

Seven infrared temperature-measuring instruments were chosen for evaluation. Three test evaluators with varied backgrounds in solar energy systems and thermographic instruments were also selected. The researchers chose three sites for the field tests: a residential air system, a residential liquid system with both a roof and ground array, and a large commercial application.

Five figures and two tables are included. An appendix defines the technical terms used in the report.

Conclusions: Less expensive thermographic equipment can be used to examine solar collector arrays. Expert infrared operators are not required to determine all system problems; however, the operators must be thoroughly familiar with solar energy systems to accurately interpret the indications. A combination of spot radiation thermometers with either a handheld imager or thermoprofile instrument is a viable inspection tool. Using thermographic techniques and equipment would greatly decrease the time and effort spent assessing reliability and performance of solar collector arrays.

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Solar Report Summary

Issued November 1982

Interim Performance Criteria for Photovoltaic Energy Systems

Richard DeBlasio

Steven Forman

Steve Hogan

Gary Nuss

Hal Post

Ronald Ross

Harry Schafft

Objective: Present interim results of work to identify and promulgate performance criteria and test methods for photovoltaic solar energy conversion systems.

Discussion: More than 50 experts in the photovoltaic field contributed to the writing and review of the 179 performance criteria listed in this document. The performance criteria address characteristics of present-day systems that are of interest to manufacturers, government agencies, purchasers, and all others interested in photovoltaic system performance and safety.

The performance criteria apply to the system as a whole and to its possible subsystems. They are categorized according to the following performance attributes: electrical, thermal, mechanical/structural, safety, durability/reliability, installation/operation/maintenance, and building/site. Each criterion con-

tains a statement of expected performance, a method of evaluation, and a commentary with further information. Over 50 references for background information are also given.

A glossary with definitions relevant to photovoltaic systems and a section on test methods are presented in two appendices. Twenty test methods are included to measure performance characteristics of subsystem elements. Three figures and two tables are included.

Conclusions: This document should assist in the acceleration of the commercialization of photovoltaic systems by offering performance criteria as a basis for standards development by voluntary consensus standards organizations. It provides a common base for both manufacturers and purchasers to use in evaluating and characterizing performance traits of systems.

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Solar Report Summary

Issued November 1982

Optical Analysis and Optimization of Parabolic Trough Collectors

P. Bendt
A. Rabi
H. W. Gaul

Objective: Summarize the results of a detailed optical analysis of parabolic trough solar collectors by a few universal graphs and curve fits.

Discussion: This report is designed to be a self-contained user's guide for optical analysis of parabolic trough collectors. The analysis method is illustrated by specific examples that are typical of practical

applications. The sensitivity of the optimization procedure to changes in collector parameters and operating conditions is evaluated.

Four figures and seven tables are included.

Conclusions: The presented graphs enable the designer of parabolic trough collectors to calculate performance and optimize the design with a simple hand calculator.

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Solar Report Summary

Issued November 1982

Performance Criteria for Photovoltaic Energy Systems

Gary Nuss
Richard DeBlasio
Alan Hoffman
Steve Hogan
Paul Longrigg
Hal Post
Ronald Ross
Harry Schafft

Objective: Define performance criteria and test methods for photovoltaic (PV) solar energy conversion systems.

Discussion: This document presents the state-of-the-art in defining performance criteria for PV systems and their components — the PV array, power conditioning, monitor and control, storage, cabling, and power distribution. A performance criterion describes a performance need or expectation that represents a characteristic of the PV system, subsystem, or component that is related to performance or safety. Each performance criterion presented consists of a criterion statement, an evaluation statement that describes how compliance with the criterion statement can be evaluated, and a commentary to provide further information or justification.

The performance criteria deal with the following seven attributes: electrical, thermal, mechanical/structural, safety, durability, reliability, installation, operation and maintenance, and building and site characteristics. They are directed not only to generic but also to specific applications, such as remote stand-alone, residential, and intermediate load centers and central stations.

Volume I presents the performance criteria. Following a brief introduction, seven major sections contain the performance criteria for the PV system and each of the six subsystems. A glossary with definitions relevant to PV systems is given in Appendix A. A subject index to the performance criteria is given.

Volume II contains thirty test methods to measure performance characteristics of the subsystem elements. For each test, the scope of the procedure; a summary of the test; the significance of the test; terminology; required apparatus and its preparation, calibration, and standardization; the test procedure; interpretation of results; reporting format; and test precision and accuracy are discussed. Relevant references are given for each test.

Volume I contains four figures and two tables. Volume II contains fifty figures and two tables.

Conclusions: The performance criteria and test methods presented provide a common base for manufacturers and purchasers to use in evaluating and characterizing PV system performance.

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Solar Report Summary

Issued November 1982

Terrestrial Solar Spectra, Solar Simulation, and Solar Cell Efficiency Measurement

R. Matson

R. Bird

K. Emery

Objective: Address the main issues in providing a reproducible terrestrial solar irradiance standard that can be used to accurately measure the conversion efficiency of solar cells.

Discussion: Three significant steps in evaluating the conversion efficiency of solar cells are to choose a terrestrial solar irradiance standard, to select the optimal light source and filtering for simulating the terrestrial solar irradiance spectrum, and to determine the effect of a spectral mismatch between the solar simulator and a given standard solar spectrum on the measured conversion efficiency of a solar cell. This report addresses each of these issues.

After a discussion of the fundamentals of light transmittance, both measured and modeled atmospheric effects on terrestrial solar spectra are discussed. Geometric effects such as global versus direct beam measurements and cell orientation are also reviewed. The SERI proposed ASTM global and direct beam terrestrial solar spectra are presented, and a detailed

evaluative review is given for a number of solar simulators. Finally, the effects of using a non-ideal light source on the measured short-circuit current and methods of calibrating the short-circuit current of a solar cell with respect to a given irradiance spectrum are discussed.

Sixty figures and seven tables are included. Appendix A defines meteorological terms used, and Appendix B treats the solar simulator used in the SERI Photovoltaic Measurement and Evaluation Laboratory. A bibliography is included for the interested reader.

Conclusions: The need for a sophisticated solar simulator is proportional to the spectral mismatch between the spectral response of the reference cell used to set the solar simulator and that of the test cell. The recently proposed ASTM terrestrial solar irradiance spectrum is recommended as a reference spectrum. Either filtered xenon-arc or dichroic filtered tungsten-halogen lamps are suggested for solar simulation.

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Issued September 1983

Development of Photovoltaic Array and Module Safety Requirements

Final Report

Underwriters Laboratories Inc.

Objective: Identify and develop module safety requirements for photovoltaic module and panel designs and configurations likely to be used in residential, intermediate, and large-scale applications.

Discussion: The National Electrical Code and Building Codes were reviewed with respect to present provisions which may be considered to affect the design of photovoltaic modules. Limited testing, primarily in the roof fire resistance field, was conducted. The generation of engineering safety requirements included a safety workshop which encompassed a broad cross section of the photovoltaic community. Comments from the workshop resulted in additional studies and further investigations which led to the development of an Underwriters Laboratories, Proposed Standard for Safety — Flat-Plate Photovoltaic Modules and Panels. Additional work covered the initial investigation of conceptual approaches and temporary

deployment, for concept verification purposes, of a differential dc ground-fault detection circuit suitable as a part of a photovoltaic array safety system.

Conclusions: To determine the adequacy or facility for implementation of the recommendations: (1) modules should be evaluated according to the proposed standard; (2) safety-related performance of modules should be monitored; and (3) the conditions of installation of modules should be evaluated to determine the effects on safety performance. Additional interaction between standards and code-writing bodies and manufacturers is needed to achieve this. Modification to the present proposals for standards and codes may be warranted depending on the observed safety-related performances. Requirements for ancillary components including blocking and bypass diodes should be prepared.

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Solar Report Summary

Issued September 1983

EMI from Solar Panels and Inverters — National Bureau of Standards

Paul Longrigg
Technical Monitor

Objective: To present results of measurements of electromagnetic interference (EMI), particularly at low frequencies, caused by power conditioning systems.

Discussion: Radiated electromagnetic fields were measured near several solar array systems at the New Mexico Solar Energy Institute, Las Cruces, New Mexico, during September 1981. The measured results show that the inverters in these systems generate strong EMI, particularly at low frequencies; e.g., in the AM broadcast band (0.5 to 1.6 MHz). The inverters generated most of the EMI in the solar-panel system. Measurements were made over the frequency range of 40 Hz to 600 MHz at distances from the inverters of 1, 10, 45, and 80 m. The levels of EMI at distances of 1 m were 50 dB above ambient at frequencies from 40

Hz to 1 MHz. At distances of 10 and 45 m, the levels were 30 to 40 dB above ambient at frequencies from 40 Hz to 6 MHz. At 80-m distances, no signals were detected above ambient. Above 30 MHz, the EMI at a 1-m distance was at most 5 dB above ambient.

Results and Recommendations: If the filtering on inverters is improved, the radiated EMI could be reduced significantly. The EMI from the inverters in the measured system rendered the AM broadcast band useless at distances of 1 to 3 m and degraded the band within a 40-m radius. Television and FM broadcast reception, however, should not be bothered, but service on some of the lower frequency bands for amateur radio service is likely to be degraded.

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Solar Report Summary

Issued September 1983

Evaluation of Conventional Electric Power Generating Industry Quality Assurance and Reliability Practices

R. T. Anderson

H. A. Lauffenburger

Objective: Determine the techniques used in the electric power generation industry that might serve as a baseline for quality assurance and reliability (QA&R) procedures for photovoltaic (PV) solar energy systems.

Discussion: Information and data were obtained from utilities, architectural and engineering firms, manufacturers, industry associations, and others active in QA&R. Discussion questions dealt with scope, organization, procedures, methods, effectiveness, and terminology of practices currently being applied. Findings were reduced, organized, and evaluated, and recommendations were formulated on the potential applicability of specific approaches to PV systems and components. Study results, conclusions,

and recommended QA&R activities for the PV program are presented in this report.

Seventeen figures and 18 tables are included. Five appendices present definitions, a discussion of the Department of Energy Fossil Energy Equipment Data System, two examples of industry approach, and a bibliography.

Conclusions: A number of specific industry practices and programs are applicable to the PV program, as detailed in the report. Major benefits can be expected, both in the immediate and long-term adaptation of selected QA&R practices to the PV program.

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Solar Report Summary

Issued September 1983

An Experimental Performance Evaluation of Line-Focus Sun Trackers

Randy C. Gee

Objective: Provide test data for and analyses of an aperture-based sun tracker and a flux-line sun tracker.

Discussion: Sun trackers are an important component in the operation of line-focus parabolic trough concentrating collectors. However, there have been many problems ranging from excessive tracker adjustment to complete failure to recognize the sun under nonideal sky conditions.

Improvements were made, and new sun tracker concepts implemented. To evaluate these sun trackers, an outdoor test stand was built at SERI. Using the stand, trackers were tested over a wide range of insolation levels, so that the measured performance

would be applicable to actual operations. Both aperture-based and flux-line sun trackers were tested.

Thirty-two figures are included. Three appendices present background mathematical details.

Conclusions: Both the flux-line and aperture-based trackers were found to have an effective rms error of about one milliradian. This error resulted in negligible effect on the performance of typical parabolic trough concentrating collectors. An analysis of the alignment problem for an aperture-based (shadow-band-type) sun tracker showed that tracker alignment can be a substantial source of tracking error.

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Solar Report Summary

Issued January 1985

Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines

David G. Stephens
Kevin F. Shepherd
Harvey H. Hubbard
Ferdinand W. Grosveld
National Aeronautics and Space Administration

Objective: Provide a guide for evaluating human exposure to wind turbine noise.

Discussion: This document is intended for use in designing and siting future large wind turbine systems and for assessing the noise environment of existing wind turbine systems. Noise source characteristics, propagation of noise to the receiver location, and the exposure of the receiver to the noise are discussed. Five appendices present background information used in preparing the guide. These appendices cover

wind turbine noise source characteristics, human perception thresholds, response of buildings to noise, atmospheric propagation, and sample calculations.

Twenty-seven figures are included.

Conclusions: The recommended goal for design and siting is to reduce the levels of noise and vibration at the receiver location below the perception thresholds of existing background noise conditions.

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Solar Report Summary

Issued June 1986

Objective: Present research comparing collector-efficiency measurements to a common set of conditions.

Discussion: The reason for determining the thermal efficiencies of solar collectors is to provide useful information for designing solar systems and for comparing the expected performance of different collectors. ASHRAE Standard 93-77A contains a method for measuring the thermal efficiency of solar collectors. The procedures in this standard are applicable to outdoor testing under specified conditions and to indoor testing using solar simulators. Both air- and liquid-type collectors are covered.

This report describes the development and testing of an analytical procedure that refers collector-efficiency measurements, obtained under different test conditions, to a standard set of conditions. The procedure applies to flat-plate, liquid-type collectors of conventional tube-in-sheet design. The basic Hottel-Whillier-Bliss theory is modified appropriately to account for serpentine-flow configurations and glazing materials with high infrared transmittance. The procedure includes a systematic method for deriving two invariant collector parameters (plate absorptance and back-loss coefficient) directly from ASHRAE Standard 93-77 test results. The author recommends a set of standard conditions that corresponds to favorable test conditions.

Solar Collector Test Procedures: Development of a Method to Refer Measured Efficiencies to Standardized Test Conditions

William C. Thomas

The report presents a detailed description of the analytical methods involved and a mathematical model for thermal performance in flat-plate collectors. A procedure for correcting results to common environmental and test conditions is also described. The experiments, including test apparatus and facilities, that were conducted to accompany the analytical research are explained and the test data are presented.

The report contains 5 tables and 35 figures. Four appendices are also presented; they contain specific system information, tabulations of data and results, and user instructions for test-correction programs.

Conclusions: The analytical procedure provides a standard methodology for deriving two invariant parameters directly from ASHRAE 93-77 test results. Also, the allowable variations in test parameters can significantly affect the measured efficiencies. Transient effects in the data, which are caused by climatic conditions, are a serious problem and cannot be reconciled by the procedure. The analytical correction procedure reduced the scatter of measured efficiencies around the correlating curve in the cases considered.

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Solar Report Summary

Issued June 1986

Objective: Present an evaluation conducted by the National Conference of States on Building Codes and Standards, Inc. (NCSBCS) on the adoption and use of building code provisions and criteria for solar energy systems.

Discussion: The recent increase in the use of solar energy systems creates an increased concern for health and life-safety issues in buildings using such systems. Some of these concerns, such as electrical connections and plumbing system designs, have been addressed for years in the building codes used throughout the United States. However, other concerns, such as the separation of potable water and toxic heat transfer fluids, have not received much attention (especially in residential construction) until the increased use of solar energy systems took place.

This report outlines the current status of the technical criteria that the code-enforcement community uses to regulate the design and installation of solar energy systems in new and existing buildings. This report contains data that the NCSBCS collected from 31 major U.S. cities and 50 states.

This report presents background on the evolution of building code provisions for solar energy systems as well as a brief description of the methodology used to obtain the data from the major cities and states. The data are presented in tabular form, and specific

Status of Building Code Provisions for Solar Energy Systems

David R. Conover

information on construction regulations and source documents is cited for each city or state. A summary of these data is also included.

Appendix A is a list of the major city and state agencies that were contacted during data collection. Appendix B presents the state evaluation forms, and Appendix C contains the major city evaluation forms.

Conclusions: The report's review of the current solar code situation indicates the following:

- The anticipated multitude of different solar codes did not materialize, and codes apparently have not stifled solar technology.
- Many states have no preemptive authority over local government and/or have codes with building, plumbing, mechanical, and electrical provisions that are applicable to all building and systems construction, though they may not be solar-specific codes.
- No federal incentive existed to cause states to enact solar code legislation as was the case with energy conservation codes.

The NCSBCS recommended five areas for further study:

- Redefine the need for solar-related code provisions addressing health and life-safety issues.

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- Determine if solar provisions are more easily developed, adopted, and enforced as part of the model code process or as separate documents.
- Document case histories of solar systems installed under various code criteria, identify problem areas, develop optimum solar code criteria, and use these results to revise existing solar code criteria.
- Review compliance and enforcement issues associated with solar code criteria and develop recommendations for more effective and efficient enforcement of solar code criteria.
- Increase the level of effort in training and education on solar systems inspection for the code community through state code and energy offices.

Solar Report Summary

Issued June 1986

Objective: Present analyses and experiments conducted to evaluate potential eye hazards of reflected heliostat beams and verify the adequacy of the beam-safety control strategy at the 10 MW_e Solar Thermal Central Receiver Pilot Plant.

Discussion: During 1981 and 1982, a beam-safety test program was conducted at the 10 MW_e Solar Thermal Central Receiver Pilot Plant in Barstow, Calif., under the sponsorship of Southern California Edison (SCE) and Sandia National Laboratories, Livermore (SNLL). The principal aims of the program were to:

- Identify and evaluate any eye hazards caused by heliostat beams at ground level and in airspace above the plant, and confirm the adequacy of the adopted beam-control strategy
- Confirm the adequacy of at least one beam-control strategy for heliostats that are designed to stow horizontally faceup in high-wind conditions
- Measure receiver brightness and determine whether it constitutes an eye hazard.

These goals were accomplished through the following three coordinated activities: analytical investigations with a special beam-safety computer code at SNLL, preliminary ground-safety tests at the pilot plant in December 1981, and the helicopter flyover and ground-safety test series conducted at the plant in August 1982. The report presents the findings of each of these stages of testing.

10 MW_e Solar Thermal Central Receiver Pilot Plant: Beam Safety Tests and Analyses

T. D. Brumleve

Two tables and 23 figures are included in the report. Appendix A contains the specifications of the pilot-plant beam-safety tests that were performed in 1982.

Conclusions: The results of the testing are described, followed by several recommendations:

- Beam-safety aspects should be considered early in the design process so that beam-control options are not limited unnecessarily by heliostat hardware or software decisions.
- The present pilot-plant beam-control strategy adequately precludes eye hazards in the airspace above an 800-ft altitude during normal plant operations.
- No need exists for a special exclusion zone above the field for aircraft complying with general FAA flight rules.
- The special expanding-ring beam-control strategy for faceup stow precludes eye hazards above 800 ft.
- The hazardous zones around the bases of the wires are approximately correct as presently delineated.
- The east and west access roads are probably safe as a practical matter but should continue to be treated as marginal during wire walks.
- The south access road to the core area is safe for the summer assignments; however, it should continue to be treated as marginal during winter wire walks.

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- The north access road and the central core area are safe at all times of the year.
- The area near the south-plant entrance gate and all ground-level areas outside the heliostat field are safe.
- The receiver is not bright enough to constitute an eye hazard for momentary viewing. It is also safe for continuous viewing, although this is not recommended.
- The measured data are consistent with previous analyses, tests, and predictions. Measurements also

confirmed that a single pilot-plant heliostat beam is safe at any distance.

- The safety measures presently in effect at the pilot plant appear to be adequate.
- An expanding-ring beam-control strategy should be considered for future central receiver plants.
- An expanding-ring strategy should be implemented, if possible, at the Barstow pilot plant.

Solar Report Summary

Issued June 1986

Solid Particle Receiver Experiments: Velocity Measurements

J. M. Hruby
V. P. Burolla

Objective: Present an evaluation of laser Doppler velocimetry (LDV) and other photometric techniques used to measure the average particle velocity in an ensemble of free-falling particles.

Discussion: As part of the technical feasibility study on the solid particle solar thermal central receiver, a diagnostic technique was developed to measure particle velocity in an ensemble of free-falling particles. This report presents the several techniques that were evaluated for particle-velocity measurement: high-speed movie photography, flash photography, and laser Doppler velocimetry. Each technique considered for particle-velocity measurement is discussed in the publication, and a detailed description of LDV is included.

After a brief introduction explaining the concept of a solid particle receiver and the experimental apparatus, a section describes the flow-field characterization techniques that were pursued for the evaluation, as well as those that were not. Section 3 consists of a

thorough description of LDV and its role in particle-velocity measurement. The fourth section presents the velocity data obtained from high-speed movie photography, flash photography, and LDV. Qualitative discussion concerning flow-field turbulence and curtain behavior is also included in this section.

The text is complemented by 20 illustrations.

Conclusions: The two techniques that proved most successful for measuring particle velocity were flash photography and LDV. The velocities obtained from these techniques agree, although the photographic technique is biased toward slow-moving particles.

Two-phased particle velocities in particle ensembles are greater than the velocity of a free-falling isolated sphere of the same effective diameter. The influx of air into the particle stream is believed to be responsible for this. Particle-particle interactions are negligible, and curtain instability occurs after one meter of fall.

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Solar Report Summary

Issued June 1986

Solid Particle Receiver Experiments: Radiant Heat Test

J. M. Hruby
B. R. Steele
V. P. Burolla

Objective: Present data collected during tests designed to evaluate the solar thermal solid particle receiver concept.

Discussion: The focus of this report is an experiment performed at the Radiant Heat Facility, Sandia National Laboratories-Albuquerque, in which free-falling particles were irradiated with infrared lamps over a 10-m fall distance. The intensity of the lamps was comparable to the solar flux at a central receiver, but spectrally different. This radiant heat experiment serves two purposes: it provides engineering information concerning particle aerodynamic and thermal behavior, and it provides data to verify analytical models. This report presents the experiments and the results that were produced.

Following a brief introduction, this publication describes the tests, including the objectives, facility

and apparatus, and diagnostics. A detailed discussion of the baseline characterization and radiant heating tests is presented, as well as sections concerning energy absorption, energy efficiency, and energy balance.

The report is well documented, with 8 tables and 16 figures. Three appendices are also included, presenting graphic information for optical property data, sample data output, and spatial flux-distribution measurements.

Conclusions: The data obtained from this experiment verify that free-falling particles can be used as the working media in a high-temperature solar central receiver. In addition, the experimental data obtained will aid in analytical model verification and receiver design.

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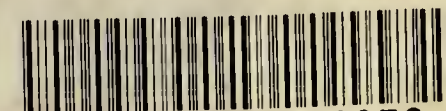
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